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& Knowledgebase

2024

Global Quantum Communication & Security Industry Development Prospect

February 2024

Quantum Annual Series Report

Foreward

In 2023, the field of quantum communication and security witnessed significant development and innovation. Through the collective efforts of major quantum-involved countries and technology enterprises worldwide, quantum technology achieved numerous breakthroughs and innovations in secure information communication, facilitating the transition of many projects from laboratory experiments to commercial applications. Events, progress, and achievements such as Google's implementation of PQC algorithms, IBM's introduction of quantum security roadmap, and the initiation of the European Union's EuroQCI project all underscored the flourishing of this domain. As a cutting-edge technology in the fields of information communication and network security, quantum communication and security not only offer new possibilities for constructing a global digital society but also lead the future of network security.

This report focuses on the comprehensive development of the quantum communication and security industry ecosystem. It examines key innovations in various technical areas such as quantum key distribution (QKD), post-quantum cryptography (PQC), and quantum random number generators (QRNG). Based on this examination, it explores the commercialization of products and their applications in the industry. The aim is to review and analyze the significant progress made in the field of quantum communication and security in 2023, and to propose ideas and viewpoints on short-term future development trends.

As an annual publication, this report does not primarily explain the basic principles of technology but rather focuses on presenting the practical applications of these technologies and products in a commercial environment. It also addresses the implementation status of significant global projects and the efforts and achievements of various parties in research and development, standardization, and commercialization. Through in-depth analysis of these aspects, we aim to provide readers with a clear picture, demonstrating the leading position and potential of the quantum communication and security industry in today's technological era.

Despite the less optimistic macroeconomic situation globally and the consecutive decline in financing in the field of quantum communication and security over the past three years, the developments in 2023 remain encouraging. Several policies have sent clear development signals to various links in the industry chain, indicating promising development opportunities in the quantum communication and security field for the coming year. While we acknowledge the need to face new challenges, let us collectively look forward to and witness the expansion and excellence of this field in the future, injecting more vitality and possibilities into secure communication in the digital age.

ICV Frontier Technology Consulting Director, Senior Vice President

Jude Green

Jude Green

Declaration

01 The content and viewpoints presented in this report strive to be independent and objective. The information or opinions expressed herein do not constitute investment advice; therefore, please exercise caution when referring to them.

02 This report aims to summarize and present significant events that occurred in the global quantum sub-sector technology and industry during the year 2023. It relies primarily on publicly available data and information, as well as the compilation of publicly accessible data. Additionally, it combines the global economic development status at the time of publication to provide predictive descriptions of potential short-term impacts.

03 This report focuses on relevant content within the quantum sub-sector industry that occurred between January 1, 2023, and December 31, 2023, based on local time reporting and the time of initial event publication. Reports of the same content or highly similar content, if spanning across different years, are not considered significant events occurring in 2023.

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01 Advancements in QKD

The mileage of QKD circuits based on optical fiber transmission is gradually increasing, laying the foundation for the construction of large-scale quantum networks

In 2023, for the first time, the distance of China's fiber-based Twin-Field Quantum Key Distribution (TF-QKD) system surpassed 1000 kilometers, reaching 1002 kilometers. This achievement represents a crucial step towards the establishment of future large-scale quantum networks. The breakthrough was validated through experiments, demonstrating the feasibility of employing the Send-and-Not-Send (SNS) protocol for TF-QKD over long-distance optical fibers

The implementation of a 615-kilometer fiber-based quantum key distribution (QKD) experiment was achieved through the coherent sideband locking and remote laser frequency calibration technology. This experiment utilized an open architecture and novel TF-QKD system that does not require service fibers. It successfully attained secure key rates over low-loss optical fibers at distances of 400 kilometers, 500 kilometers, and 600 kilometers, surpassing the rate limits of unrelayed QKD. Additionally, the experiment demonstrated successful quantum key distribution with arm length differences of up to one hundred kilometers.

The increase in QKD key transmission rates once again facilitates more frequent key exchanges, thereby enhancing the security and efficiency of cryptographic communications

By advancing key technologies such as high-fidelity integrated photonics for quantum state manipulation and high-count-rate superconducting single-photon detection, it is possible to achieve real-time quantum key distribution at a rate of 100 megabits per second (115.8 Mbps). This experimental result represents a significant increase in the achievable key rates, surpassing previous records by an order of magnitude.

nature photonics
中国科学技术大学 University of Science and Technology of China
JIQT 济南量子技术研究院 Jinan Institute of Quantum Technology
哈爾濱工業大學 HARBIN INSTITUTE OF TECHNOLOGY

The new transmission record is established based on novel QKD encryption theories, which alleviate previous limitations on distance and data transfer rates in quantum secure communication. Leveraging conventional optical fibers and optical amplifiers, it becomes feasible to achieve quantum secure communication over distances exceeding 1032 kilometers in optical fiber cables, with a data transfer rate (key rate) significantly higher than previous records (previously: 0.0034 bits per second; now: 34 bits per second).

arXiv
Terra Quantum

The integration of sky-ground entangled-link QKD, resilient to strong background noise, lays a solid foundation for the development of integrated sky-ground communication networks.

The latest demonstration of hybrid-link Quantum Key Distribution (QKD) technology, featuring continuous operation and resilience to strong background noise, has been successfully completed. This technology combines space-based and fiber-based links to achieve Hong-Ou-Mandel (HOM) interference. Even in conditions where the traditional BB84 protocol cannot operate properly, this technology is capable of effectively performing Multi-Dimensional Interference Quantum Key Distribution (MDI-QKD). Furthermore, researchers have delved into the feasibility of satellite-based HOM interference, laying crucial groundwork for the establishment of integrated sky-ground hybrid communication networks.

PHYSICAL REVIEW LETTERS
中国科学技术大学 University of Science and Technology of China
清華大学 Tsinghua University
中国科学院 CHINESE ACADEMY OF SCIENCES

QKD achieves secure key generation over long distances, effectively reducing the complexity of protocol implementation.

The Mode-Matching Quantum Key Distribution (MP-QKD) protocol, utilizing maximum likelihood estimation for post-processing data, precisely estimates the frequency difference of two independent lasers for parameter estimation. This achieves secure key generation over laboratory-standard optical fibers at distances of hundreds of kilometers, including 100 km, 200 km, 300 km, and ultra-low-loss optical fibers at 400 km. Compared to previous MDI experiments, there is a significant improvement in the key generation rate, with a three-order-of-magnitude increase in the key generation rate at distances of 300 km and 400 km.

PHYSICAL REVIEW LETTERS
中国科学技术大学 University of Science and Technology of China
清华大学 Tsinghua University
国盾量子 QuantumCTek

The application of "asynchronous matching" technology in quantum communication greatly improves the key rate and combines the advantages of both "twin-field" and "measurement-device-independent" protocols. This results in a simpler quantum communication architecture, enabling communication over longer distances. The use of asynchronous matching improves the measurement-device-independent (MDI) quantum key distribution scheme, allowing it to break the key rate-transmission loss relationship while simplifying the structure. Key generation rates achieved are 57 kbps @ 201 km, 5 kbps @ 306 km, 590 bps @ 413 km, and 42.64 bps @ 508 km.

PHYSICAL REVIEW LETTERS
北京量子信息科学研究院 Beijing Academy of Quantum Information Sciences
南京大學 NANJING UNIVERSITY

02 Advancements in QRNG

Combining quantum non-locality, quantum-safe algorithms, and zero-knowledge proofs enhances the security of non-interactive zero-knowledge proofs.

Chinese scientists have achieved a breakthrough by integrating quantum non-locality, quantum-safe algorithms, and zero-knowledge proofs (ZKPs) to create a novel system. This system utilizes device-independent quantum random number generators as entropy sources and employs post-quantum cryptography for identity authentication in the generation of random number beacons for public services. By applying this system to the field of non-interactive zero-knowledge proofs (NIZKPs), they have effectively addressed the security vulnerabilities arising from the challenges of implementing true random numbers in NIZKPs. As a result, the security of NIZKPs has been significantly enhanced.

To enhance the output rate of raw random sequences and achieve high randomness, it is crucial to develop high-speed QRNGs.

The discrete-type Quantum Random Number Generator (QRNG), utilizing the avalanche photodiode electron tunneling effect, achieves a raw random sequence output rate of 100 Mbps under standard temperature and pressure conditions. With a statistical minimum entropy of 0.9944 bits/bit based on 8,000,000 bits and NIST SP 800-90B certification yielding a minimum entropy of 0.9872 bits/bit, this QRNG enables the continuous output of high-randomness random numbers without any post-processing for extended periods.

Moreover, significant progress has been made in maintaining high randomness over long continuous periods in the output of raw data from this QRNG. The system achieved continuous stable output of 1,174 Gbits of raw data over 11,744 seconds, with a statistical minimum entropy distribution of 0.9892 bits/bit for each 8 Mbits as the basic unit.

Use particles and antiparticles to increase the rate of quantum random number generation.

Generating random numbers using quantum vacuum states typically comes with speed limitations. Researchers have therefore developed a quantum random number generator by leveraging the behavior of particle-antiparticle pairs. They found that its speed is 200 times faster than traditional systems, achieving a generation rate of 100 Gbit per second in experiments. This marks a significant advancement in the speed of vacuum-based quantum random number generation.

PRX Quantum

Politecnico di Bari

DTU Technical University of Denmark

UNIVERSITEIT GENT

03 Advancements in PQC

The current focus in the field of Post-Quantum Cryptography (PQC) algorithms primarily revolves around the evaluation of algorithmic security, including resistance against quantum attacks, difficulty of mathematical problems, resistance against side-channel attacks, and other aspects. Therefore, various parties predominantly assess different PQC algorithms within the framework provided by NIST to ensure that PQC algorithms can effectively withstand threats from quantum computing in commercial applications.

The Kyber Key Encapsulation Mechanism (KEM) is an encryption standard nominated by NIST to protect networks from future quantum computer attacks. However, in 2023, KEM encountered consecutive security vulnerabilities. In December, researchers from the cybersecurity company Cryspen explained two vulnerabilities in this algorithm, known as KyberSlash 1 and KyberSlash 2, both of which are time-based attacks. Attackers can infer the time of each attempt by observing the specific division operation executed during the decryption process of Kyber, enabling them to reverse engineer and crack the algorithm. This attack method falls under side-channel attacks and can be used to disrupt any type of encryption, including classical algorithms and PQC algorithms.

At the beginning of 2023, the Royal Institute of Technology in Sweden successfully cracked the NIST-nominated Crystals-Kyber algorithm solely using a neural network, marking the fourth time a PQC algorithm has been compromised.

Currently, public concerns regarding the security of PQC algorithms have gradually shifted from theoretical mathematical vulnerabilities to more practical considerations, specifically focusing on potential attacks in real-world scenarios. The emergence of real-world attacks emphasizes the importance of timely inspection and remediation of potential vulnerabilities when deploying PQC algorithms, prompting continuous improvement and evolution of PQC algorithms to enhance security in real-world application scenarios.

While the migration towards PQC is progressing, rigorous assessment of the security of PQC algorithms remains necessary.

The novel neural network training method, "Recursive Learning," achieves side-channel attacks on the highest 5th-order mask of the Crystals-Kyber algorithm among the four PQC algorithms published by NIST with over 99% probability of recovering the message bit by cyclically rotating information. This discovery underscores the importance of security evaluations for PQC algorithms, indicating that neural networks alone can crack NIST's PQC algorithms.

Cryptology ePrint Archive

04 Advancements in QT

Utilizing multiplexed quantum memories to achieve long-distance quantum teleportation.

Quantum teleportation (QT) is a fundamental capability in quantum networks, enabling the transfer of quantum bits without direct exchange of quantum information. The experiment demonstrates a method for long-distance quantum transmission, transferring quantum bits from photonic qubits in the communication band to material qubits stored in solid-state quantum memories, achieving quantum teleportation of information over 1 kilometer utilizing multiplexed quantum memories. The system employs an active feed-forward scheme, satisfying the protocol requirements by applying conditional phase shifts to the retrieved quantum bits from the memory. Unique to this approach is the utilization of time-division multiplexing, which not only enhances the transmission rate but also ensures compatibility with existing telecommunication networks. These key features render this technology potentially scalable and practically deployable in the advancement of long-distance quantum communication.

Achieving high-fidelity continuous-variable quantum teleportation by noiseless linear amplification.

nature communications

Australian National University

In order to overcome the limitations in fidelity and transmission distance associated with continuous-variable quantum teleportation, we developed a noiseless linear amplifier-based heralded quantum teleporter to address these constraints. By utilizing moderately entangled coherent states for transmission, we achieved a high fidelity of 92%. Our teleporter fundamentally allows for the nearly complete elimination of losses caused by transmitting input states through imperfect quantum channels. Additionally, we demonstrated the purification of displaced thermal states, a task unattainable with conventional deterministic amplification or transmission methods. The combination of high-fidelity coherent-state transmission with purification of thermalized input states enables the transmission of quantum states over considerable distances. This experiment overcomes longstanding barriers to efficient continuous-variable quantum transmission and provides new insights into applying transmission for purifying quantum systems from thermal noise.

05 Advancements in Commercial Application

Quantum communication has achieved interdisciplinary integration with quantum computation and quantum precision measurement.

Companies such as IBM and Quantinuum, due to their remarkable achievements in the field of quantum computing, are often perceived as companies focused solely on quantum computing. However, the current research and business strategies of these companies are no longer confined to the field of quantum computing. They have released roadmaps for development in the field of quantum communication and security or introduced related products and solutions.

In May, IBM released a quantum security roadmap, which includes steps that organizations/companies can take to implement quantum communication and security. Additionally, IBM introduced a comprehensive set of solutions called IBM Quantum Safe to support the implementation of quantum security roadmap. IBM Quantum Safe comprises IBM Quantum Safe Explorer, IBM Quantum Safe Advisor, and IBM Quantum Safe Remediator. This technology consists of three key operations: discovery (identifying encryption usage, analyzing dependencies, and generating an inventory of cryptographic materials), observation (analyzing the cryptographic posture of vulnerabilities and determining the priority of remediation measures based on risk), and transformation (repairing and mitigating through encryption agility and built-in automation). In 2022, IBM announced plans to launch a quantum processor named "Kookaburra" in 2025. Kookaburra is a 1386-qubit multi-chip processor with quantum communication links. IBM will connect three Kookaburra chips into a 4158-qubit system linked by quantum communication.

IBM Q™

Quantinuum introduced Quantum Origin Onboard, a commercially available enterprise software solution that provides quantum computing-enhanced key strengthening. It can be directly installed on devices and used to provide foundational protection, integrating directly into connected devices without the need for additional hardware upgrades. This unique approach ensures that devices in any environment, whether online or offline, can generate quantum computing-enhanced keys, continually maximizing the strength of encryption measures to protect the device.

QUANTINUUM

The US quantum computing company QCI began expanding its commercial product line in April, introducing reprogrammable and non-repeating QRNG.

QCi Innovative Quantum Solutions Company

Enterprises are collaborating to drive the implementation of quantum encryption in critical infrastructure.

Securing critical infrastructure is paramount to enhancing network defense capabilities and ensuring the security of data and systems. For instance, Honeywell leverages Quantinuum's Quantum Origin technology to generate keys with enhanced randomness through quantum computing, making them truly unpredictable. This protects user data of smart meters and critical infrastructure from advanced cybersecurity threats, helping utility sectors undergoing digital transformation to enhance reliability and trust.

Honeywell

QUANTINUUM

In Wuhan Economic and Technological Development Zone, China State Grid Wuhan Power Supply Company has successfully implemented quantum encrypted communication in the power distribution automation terminals within its supply network, marking the first successful application of quantum encryption technology in the power grid in Hubei Province. Quantum encrypted communication modules are installed in newly added communication lines, with each distribution device equipped with a quantum encrypted communication module. This enables quantum encrypted communication through communication links connected to the power grid.

国家电网 STATE GRID

The commercially configurable quantum network software is officially open to quantum developers.

The EPB Quantum Network, launched jointly by the American broadband service provider EPB in collaboration with quantum companies Qubitekk and Aliro Quantum, is now open to customers. It stands as the first commercially configurable quantum network in the United States, specifically designed for quantum technology firms and researchers, aiming to eliminate commercialization barriers for quantum developers.

The EPB Quantum Network functions as a quantum-as-a-service product, offering fiber optic infrastructure and software to quantum technology professionals, expediting the process of bringing quantum technologies and applications to market. Customers can utilize state-of-the-art foundational quantum equipment to generate, distribute, and measure quantum bits via dedicated fiber optics within the EPB Quantum Network. The network is now open to customers, allowing users to specify parameters for a range of network configurations they require. They can utilize AliroNet TM, designed and manufactured by Aliro Quantum, to build, test, validate, characterize, and operate their products, offering control and configuration capabilities.

The real-time satellite quantum resilient encryption link in space has been successfully completed.

The United States has initiated satellite data transmission based on real-time, end-to-end quantum resilient encryption communication satellite space links. This satellite link, completed through a collaboration between QuSecure and Accenture, employs PQC to protect multi-orbit data communication. It establishes encrypted quantum resilient channels from Earth to low Earth orbit satellites. Additionally, it can switch to geosynchronous satellites and transmit back to Earth, thereby simulating a redundant backup plan in case a satellite on a single orbit encounters threats, faults, or attacks. The entire transmission is safeguarded using traditional network security measures along with QuSecure's QuProtectTM platform for quantum resilient network security.

The construction of the European Quantum Communication Infrastructure has commenced.

The European Commission, in collaboration with 27 EU member states and the European Space Agency (ESA), is working on the design, development, and deployment of the European Quantum Communication Infrastructure (EuroQCI) project. EuroQCI consists of two parts: the ground segment comprising fiber optic communication networks connecting national and cross-border strategic sites, and the space segment based on satellite technology. The EuroQCI initiative was launched in 2019 with the EuroQCI Declaration, initially signed by seven member states. By July 2021, with Ireland's signature, all 27 EU countries have joined EuroQCI. EuroQCI aims to deploy quantum communication infrastructure throughout the EU and its overseas territories by 2027. The project is supported by the coordination organization PETRUS, whose members include DT (Deutsche Telekom), Airbus, Thales, and AIT (Austrian Institute of Technology).

Regarding the ground construction phase, the first implementation phase of EuroQCI began in January 2023 and is expected to last for 30 months, concluding in June 2025. Currently, several countries including Malta, Ireland, Spain, France, Denmark, and Bulgaria have initiated the construction of quantum communication infrastructure.

In the space domain, the European Commission is collaborating with the European Space Agency (ESA) to develop specifications for the first-generation EuroQCI satellite constellation. This satellite is being developed by ESA and an industrial alliance based on the first prototype satellite, Eagle-1, with a planned launch expected by late 2025 or early 2026. In November 2023, European satellite company SES led the development of the quantum-safe space-based EAGLE-1 system, closely collaborating with ESA, with TNO and Airbus joining to design and build optical ground stations for the mission.

The commercialization of PQC products has become increasingly diverse and robust.

Multiple quantum communication companies have successively proposed post-quantum cryptography (PQC) solutions, customizing and continuously optimizing them to meet the specific needs of various industries and organizations. Presently, companies such as Google, Sandbox AQ, QuSecure, WISeKey, and Xiphera are focusing on PQC solution research, providing higher levels of security for enterprise and government data. PQC products are still in the early stages of development and exploration, mostly undergoing research and testing by enterprises. At the same time, the application of PQC products also has certain limitations, primarily focusing on end-to-end secure encryption.

In the United States, there is a growing trend toward PQC adoption in mobile communication applications. QuSecure has introduced QuProtect software, leveraging quantum-secure encryption technology to ensure the security of data transmission. In July 2023, QuProtect software became available for distribution through Amazon's brand and ecosystem platform. During the same month, the telecommunications company Verizon partnered with Sandbox AQ to test quantum-secure virtual private networks (VPNs) for smartphones. In this project, Verizon utilized new technology and custom Sandbox AQ software to establish the first quantum-secure VPN, testing quantum-secure internet protocols and analytics by adjusting standard smartphones. Verizon and Sandbox AQ assessed the latest NIST standards in real-world telecommunications scenarios.

Additionally, Chrome introduced a quantum-hybrid key exchange mechanism in its latest version (version 116). This browser version added the X25519Kyber768 algorithm, resistant to quantum attacks, alongside the already deployed X25519 elliptic curve algorithm. Google's initiative represents the first opportunity for users to utilize PQC on HTTPS web pages from an organizational security standpoint.

In the UK, there is simultaneous adoption of PQC algorithms, with the launch of quantum-secure VPNs. In November, LTIMindtree launched quantum-secure virtual private network (VPN) connections in London. This quantum-secure VPN, implemented through collaboration between LTIMindtree, Quantum Xchange, and Fortinet, utilizes quantum-based key generation and out-of-band key transmission, secured by PQC algorithms to enhance the security and integrity of encrypted data.

In Switzerland, WISeKey's subsidiary SEALSQ developed an AI-based PQC quantum solution in June 2023. This solution utilizes the NIST-approved Kyber and Dilithium CRYSTAL algorithms to ensure communication security and has created the first quantum-resistant USB demonstrator.

The downstream application scenarios of PQC are gradually expanding.

In the field of communications, several companies have developed quantum-resilient encrypted satellite links. For example, QuSecure in the United States has introduced the first real-time end-to-end satellite encryption communication link with quantum resilience. This signifies that satellite data transmission in the United States now utilizes post-quantum cryptography (PQC) to withstand classical and quantum decryption attacks, thereby safeguarding the security of satellite data communication. Thales has integrated PQC applications into its flagship mobile security application, "Cryptosmart," using 5G SIM cards to implement PQC. Hybrid cryptography, which combines classical cryptography with PQC, is employed for telephone calls between two devices to protect the information exchanged during the calls.

Furthermore, various military agencies such as the U.S. federal government, the U.S. Army, the Defense Information Systems Agency (DISA), and the French Ministry of Armed Forces are seeking PQC services to ensure the security of sensitive data. In the realm of PQC, government and military agencies are increasingly inclined to collaborate with private enterprises. Private enterprises often possess faster innovation speeds and more flexible research and development capabilities. Therefore, through collaboration, government and military agencies can more swiftly acquire the latest PQC solutions.

Using QKD in combination with PQC dedicated line services ensures communication security.

In 2023, there were relatively few research papers on the fusion of PQC and QKD. However, commercial applications combining the two have emerged. Republic of Korean Internet service provider SK Broadband introduced Republic of Korea's first dedicated line service supporting both QKD and PQC online security methods. Customers can choose and utilize QKD or PQC based on their specific needs. This service has been certified by the Korean Cryptographic Module Validation Program (KCMVP). In this dedicated line service, customers have the autonomy to select the usage of QKD and PQC. SK Broadband has indicated that dedicated QKD lines exhibit excellent security performance, suitable for large clients such as governments, public institutions, medical centers, and financial institutions. On the other hand, small and medium-sized enterprises (SMEs) can opt for PQC, which does not require the installation of separate equipment. Of course, both methods can also be flexibly combined. Taking the example of biometric authentication security in banks, QKD technology can be employed within the bank's internal data center, while PQC technology can be used between customers' smartphones and authentication servers to protect biometric information. This integrated approach leverages the advantages of QKD in dedicated scenarios while fully utilizing the convenience of PQC in SMEs.

Several telecommunications operators have introduced products in this field.

Currently, telecommunication operators are actively exploring commercialization pathways for quantum communication and security technologies. These efforts include developing encrypted communication products based on quantum communication technology, integrating quantum random number generators into cloud services, and developing quantum-secure communication solutions. The introduction of these products and services signifies a significant step for quantum communication technology to transition from the laboratory to the market. However, the current commercial penetration rate is still relatively low, with the user base primarily targeting specific sectors. Increased awareness and acceptance of new products and technologies by purchasers are necessary. Telecommunication operators are working diligently to drive the commercialization process of quantum communication technology. They are collaborating with quantum technology companies or research institutions while developing more practical and cost-effective quantum products and services.

Figure: Global Communication Operators Release Quantum Communication and Security Products/Services in 2023

No.	Country	Operator	Product/Service
1	China	China Telecommunications Corporation	• Quantum security cloud • Quantum Secure Optical Transport Network (OTN) • Quantum secure communication • Customized Terminals: The Huawei Mate60 Pro Quantum Secure Communication Customized Terminal; Samsung W24 | W24 Flip mobile terminals with Quantum Secure Communication capability; and the Tianyi Platinum S9 and Tianyi Platinum 10 mobile terminals that support Quantum Secure Communication. • Quantum cryptography solutions
2		China Union Communication Corporation	• Quantum cloud shield products • Multi-scenario quantum secure communication solution
3	UK	British Telecommunications	• Quantum secure virtual private network (VPN) communications
4	Republic of Korea	SK Telecom	• Galaxy Quantum 4

QRNG suitable for space has been launched, helping to achieve quantum communication satellites.

British company Quantum Dice and Singaporean quantum communication technology company SpeQtral have jointly launched the Zenith QRNG, a device specifically designed for space applications. This device is intended to support secure quantum communication technology for the planned SpeQtral-1 satellite mission.

The Zenith QRNG is Quantum Dice's first space product, offering a high-speed, robust, and low Size, Weight, and Power (SWaP) solution. It utilizes Quantum Dice's proprietary DISC TM protocol and provides data rates ranging from 200 to 1000 Mbps. Previously, Quantum Dice's DISC ™ QRNG series boasted a random number generation rate of 7.5 Gbps.

06 Advancements in Standardization Work

Standardization process for PQC is progressing steadily.

The most influential global initiative in Post-Quantum Cryptography (PQC) standardization is led by the National Institute of Standards and Technology (NIST) of the United States. NIST has been spearheading this effort from the first round of PQC algorithm solicitation in 2017 to the announcement of the fourth round of candidates in 2022. Through four rigorous rounds of selection, NIST published draft standards for three algorithms in August 2023, which are expected to be formally approved in 2024 after public review. The release of NIST's PQC draft standards signifies the availability of multiple solutions to address the threat of quantum computing. The three algorithms covered in the published draft standards are CRYSTALS-Kyber, CRYSTALS-Dilithium, and SPHINCS+. The fourth PQC draft standard, FALCON, is expected to be released in 2024.

Figure: Timeline of PQC Project Led by NIST

Year			
2016	**Feb 2016** NIST speech at PQCrypto2016: Solicitation notice and outline from NIST	**Apr 2016** NIST releases PQC report	**Dec 2016** NIST releases official call for proposals on PQC
2017	**Nov 2017** NIST speech at PQCrypto2016: NIST issues call for proposals and outline	**Dec 2017** Results of the first round of PQC algorithm submissions announced, totaling 69 algorithms	
2018	**Apr 2018** The first PQC standardization conference convened		
2019	**Jan 2019** The second round of candidates is announced, totaling 26 algorithms	**Mar 2019** The second round of update package submission deadline	**Aug 2019** The second PQC standardization conference was held
2020	**Jul 2020** The third round of candidates was announced, featuring 7 "finalists" and 8 "candidates."	**Oct 2020** The third round of update package submission deadline	
2021	**Jun 2021** The third PQC standardization conference was held		
2022	**Jul 2022** Standardization candidates and the fourth round candidates announced	**Oct 2022** The fourth round of update package submission deadline	**Nov 2022** The forth PQC standardization conference was held
2023	**Aug 2023** Three FISP drafts released for public comment		
Further	**Apr 2024** The fifth PQC standardization meeting will be held		

International organizations have issued multiple standards for quantum communication and security.

In terms of security standards development, the European Telecommunications Standards Institute (ETSI) released the Security Assurance Framework (PP) for QKD Module Security Evaluation (GS QKD 016 V1.1.1), providing guidance for the implementation of QKD physical systems. The International Organization for Standardization (ISO) led the development of ISO/IEC 23837-1:2023 and ISO/IEC 23837-2:2023, which took five years to compile and were finally released in August.

The International Telecommunication Union Telecommunication Standardization Bureau (ITU-T) approved five QKD network protocol-related standards, including the Protocol Framework for QKD Networks (Q.4160), Ak Interface Protocol (Q.4161), Kq-1 Interface Protocol (Q.4162), Kx Interface Protocol (Q.4163), and Ck Interface Protocol (Q.4164). These five standards were jointly initiated by China, Japan, and Republic of Korea in 2021. As the first batch of international standards related to QKD network protocols, these five standards comprehensively review the protocol framework of QKD networks. They standardize aspects such as key output, key acquisition, key relay, and routing control related interface protocols in terms of protocol flow, message parameters, etc., providing specific message format references and strong technical support for the interconnection of QKD networks. Additionally, more than ten standards related to QKD network gateway nodes, interconnection nodes, network architecture, information technology, and service quality have been published (including supplementary documents).

Figure: The Development of International Quantum Communication and Security Industry Standards in 2023

No.	Release Time	Project Number	Publishing Organization	Standard Title	Supporting Members
1	Apr 2023	GS QKD 016 V1.1.1	ETSI	Quantum Key Distribution (QKD); Common Criteria Protection Profile - Pair of Prepare and Measure Quantum Key Distribution Modules	ROHDE & SCHWARZ, NPL, Institut Mines-Telecom, Facultad de Informatica, NICT, INRIM, Univ. of Waterloo, IDQ, HUAWEI TECH. GmbH, Toshiba, IDQ Europe
2	Aug 2023	ISO/IEC 23837-1:2023	ISO	Security requirements, test and evaluation methods for quantum key distribution Part 1: Requirements	/
3	Aug 2023	ISO/IEC 23837-2:2023	ISO	Security requirements, test and evaluation methods for quantum key distribution Part 2: Evaluation and testing methods	/
4	Jan 2023	Y.3813	ITU-T	Quantum key distribution networks interworking - functional requirements	BUPT, CAS Quantum Network, QuantumCTek,MIIT, China
5	Jan 2023	Y.3814	ITU-T	Quantum key distribution networks - functional requirements and architecture for machine learning enablement	BUPT, China, CAS Quantum Network., China, QuantumCTek, CAICT, MIIT PRC, ETRI.
6	Mar 2023	Suppl. 74 to ITU-T Y.3800-series	ITU-T	Standardization roadmap on Quantum Key Distribution Networks	UK, Canada, Korea (Republic of), KT, KAIST, SK Telecom, QuantumCTek, CAS Quantum Network
7	Nov 2023	Supplement 79 to ITU-T Y.3800-series	ITU-T	Quantum key distribution networks - Role in end-to-end cryptographic services with non-quantum cryptography	KT corp, KAIST, ETRI
8	Nov 2023	Supplement 80 to ITU-T Y.3800-series	ITU-T	Quantum key distribution networks use cases	Korea (Rep. of), KT Corp, ETRI, KAIST, Korea Univ., CAS Quantum Network, QuantumCtek , BUPT
9	Sep 2023	Y.3818	ITU-T	Quantum key distribution networks interworking - architecture	BUPT,CAS Quantum Network, QuantumCTek, MIIT, SK Telecom

No.	Release Time	Project Number	Publishing Organization	Standard Title	Supporting Members
10	Sep 2023	Y.3817	ITU-T	Quantum key distribution networks interworking - Requirements of quality of service assurance	Korea (Rep. of), ETRI, KT corp
11	Sep 2023	Y.3816	ITU-T	Quantum key distribution networks - Functional architecture enhancement of machine learning based quality of service assurance	ETRI, KT corp., Korea Univ., and Wuhan Rayton Networks
12	Sep 2023	Y.3815	ITU-T	Quantum key distribution networks - overview of resilience	BUPT, CAS Quantum Network, CAICT, MIIT PRC, QuantumCTek
13	Nov 2023	Y.3814 (2023)Amd 1 (ex Y.3814)	ITU-T	Quantum key distribution networks - Functional requirements and architecture for machine learning enablement	NICT, NEC, Toshiba, ETRI, CAS Quantum Network, QuantumCtek, KT, SK Telecom
14	Nov 2023	Y.3802 (2020) Amd1	ITU-T	Quantum key distribution networks - Functional architecture	NICT, NEC, Toshiba, ETRI, CAS Quantum Network, QuantumCtek, KT, SK Telecom
15	Nov 2023	Y.3803 (2020) Amd1	ITU-T	Quantum key distribution networks - Key management	NICT, NEC, Toshiba, ETRI, CAS Quantum Network, QuantumCtek, KT, SK Telecom
16	Nov 2023	Y.3804 (2020) Amd1	ITU-T	Quantum key distribution networks - Control and management	NICT, NEC, Toshiba, ETRI, CAS Quantum Network, QuantumCtek, KT, SK Telecom
17	Nov 2023	Y.3805 (2021) Amd1	ITU-T	Quantum key distribution networks - Software-defined networking control	NICT, NEC, Toshiba, ETRI, CAS Quantum Network, QuantumCtek, KT, SK Telecom
18	Nov 2023	Y.3811 (2022) Amd1	ITU-T	Quantum key distribution networks - Functional architecture for quality of service assurance	NICT, NEC, Toshiba, ETRI, CAS Quantum Network, QuantumCtek, KT, SK Telecom

No.	Release Time	Project Number	Publishing Organization	Standard Title	Supporting Members
19	Dec 2023	Y.3819	ITU-T	Quantum key distribution networks Requirements and architectural model for autonomic management and control enablement	BUPT, CAS Quantum Network, QuantumCTek,CAICT, MIIT PRC, ETRI, Korea Univ.
20	Dec 2023	Q.4160	ITU-T	Quantum key distribution networks - Protocol framework	NICT, NEC, Toshiba, ETRI, NICT, NEC, Toshiba, QuantumCTek, CAS Quantum Network, MIIT PRC, BUPT
21	Dec 2023	Q.4161	ITU-T	Protocols for Ak interface for quantum key distribution network	QuantumCTek, CAS Quantum Network, MIIT PRC, NICT, NEC, Toshiba
22	Dec 2023	Q.4162	ITU-T	Protocols for Kq-1 interface for quantum key distribution network	QuantumCTek, CAS Quantum Network, MIIT PRC, NICT, NEC, Toshiba
23	Dec 2023	Q.4163	ITU-T	Protocols for Kx interface for quantum key distribution network	NICT, NEC, Toshiba, QuantumCTek, CAS Quantum Network, MIIT PRC
24	Dec 2023	Q.4164	ITU-T	Protocols for Ck interface for quantum key distribution network	NICT, NEC, Toshiba, QuantumCTek, CAS Quantum Network, MIIT PRC
25	Dec 2023	Q.4164	ITU-T	Protocols for Ck interface for quantum key distribution network	NICT, NEC, Toshiba, QuantumCTek, CAS Quantum Network, MIIT PRC

There are still multiple quantum communication and security standards under research and development.

In the field of quantum random number generators, China has initiated the development of the national standard "General Requirements for Device-Independent Quantum Random Number Generators". This standard will clarify the terminology, structural composition, specify functional requirements, and outline performance testing methods for such products, providing guidance for both production and usage.

Regarding QKD network standards, the ITU-T's SG13, SG17, and SG11 study groups have launched over ten new standardization projects. These projects cover various aspects including the interconnection of QKD networks, definitions of intra-network and inter-network interfaces and protocols, and the security framework for trusted relay nodes.

Figure: Global Standards under Development in the Field of Quantum Communication and Security in 2023

No.	First registration	Project Number	Publishing Organization	Standard Title	Supporting Members
1	Mar 2023	20230192-T-469	CCSA	General requirements of device-independent quantum random number generator	JIQT, CAS Quantum Network, CAS Quantum Network (Shandong), USTC, THU, SITU, SUSTC, The PLA Information Engineering Univ., CAM, ISCAS, SIMIT, QuantumCTek
2	Jan 2023	Q.QKDNi_KM	ITU-T	Protocols for interfaces between key managers for quantum key distribution network interworking	NICT, NEC, Toshiba, Quantum CTek, ETRI
3	Mar 2023	Y.QKDN-qos-auto-rq	ITU-T	Quantum key distribution networks - Requirements for autonomic quality of service assurance	BUPT,CAS Quantum Network Co., Ltd,CAICT,MIIT. P.R. China, University of Science and Technology Beijing
4	Mar 2023	Y.QKDN-rsrq	ITU-T	Requirements for quantum key distribution network resilience	BUPT, CAS Quantum Network, USTB, CAICT, MIIT
5	Mar 2023	Y.QKDN-TSNfr	ITU-T	Framework for integration of quantum key distribution network and time sensitive network	University of Science and Technology Beijing, CAS Quantum Network, BUPT, QuantumCTek
6	Mar 2023	Y.supp.QKDN_sync	ITU-T	Analysis of Time Synchronization in Quantum Key Distribution Networks	MIIT China, USTB, CAS Quantum Network, QuantumCTek, BUPT, CICT

No.	First registration	Project Number	Publishing Organization	Standard Title	Supporting Members
7	Mar 2023	X.sec_QKD_profr	ITU-T	Framework of quantum key distribution (QKD) protocols in QKD network	Germany, Singapore (Republic of), CAS Quantum Network, ID Quantique, NICT, QuantumCTek, SK Telecom, National Univ. of Singapore
8	May 2023	Q.QKDN_Mk	ITU-T	Protocols for interfaces on quantum key distribution network manager	NICT, NEC, Toshiba, ETRI, QuantumCTek
9	May 2023	Q.QKDNi_profr	ITU-T	Quantum key distribution networks Interworking - Protocol framework	NICT, NEC, Toshiba, ETRI, QuantumCTek
10	Sep 2023	X.1715Amd1	ITU-T	Security requirements and measures for integration of quantum key distribution network and secure storage network	/
11	Nov 2023	Y.QKDNi-qos-fa	ITU-T	Quantum key distribution networks interworking - Functional architecture for quality of service assurance	Korea (Rep. of), ETRI, KT Corp., KAIST, Korea Univ.
12	Nov 2023	Y.QKDN-nq-qos-rf	ITU-T	Quantum key distribution networks - Requirements and framework of quality of service assurance for end-to-end QKDN and non-quantum cryptography services	ETRI, KT Corp., KAIST, Korea Univ., Korea (Rep. of), BUPT, Wuhan Rayton Network Technology
13	Nov 2023	Y.QKDN-da	ITU-T	Quantum key distribution networks - Dependability assessment	China Telecom (China), ETRI (Korea), University of Science and Technology Beijing (China), MIIT China, CAS Quantum Network (China)
14	Nov 2023	Y.QKD-TLS	ITU-T	Quantum Key Distribution integration with Transport Layer Security 1.3	Korea (Rep. of), ETRI, KT corp., KAIST, Korea Univ.

02

Industrial Ecosystem

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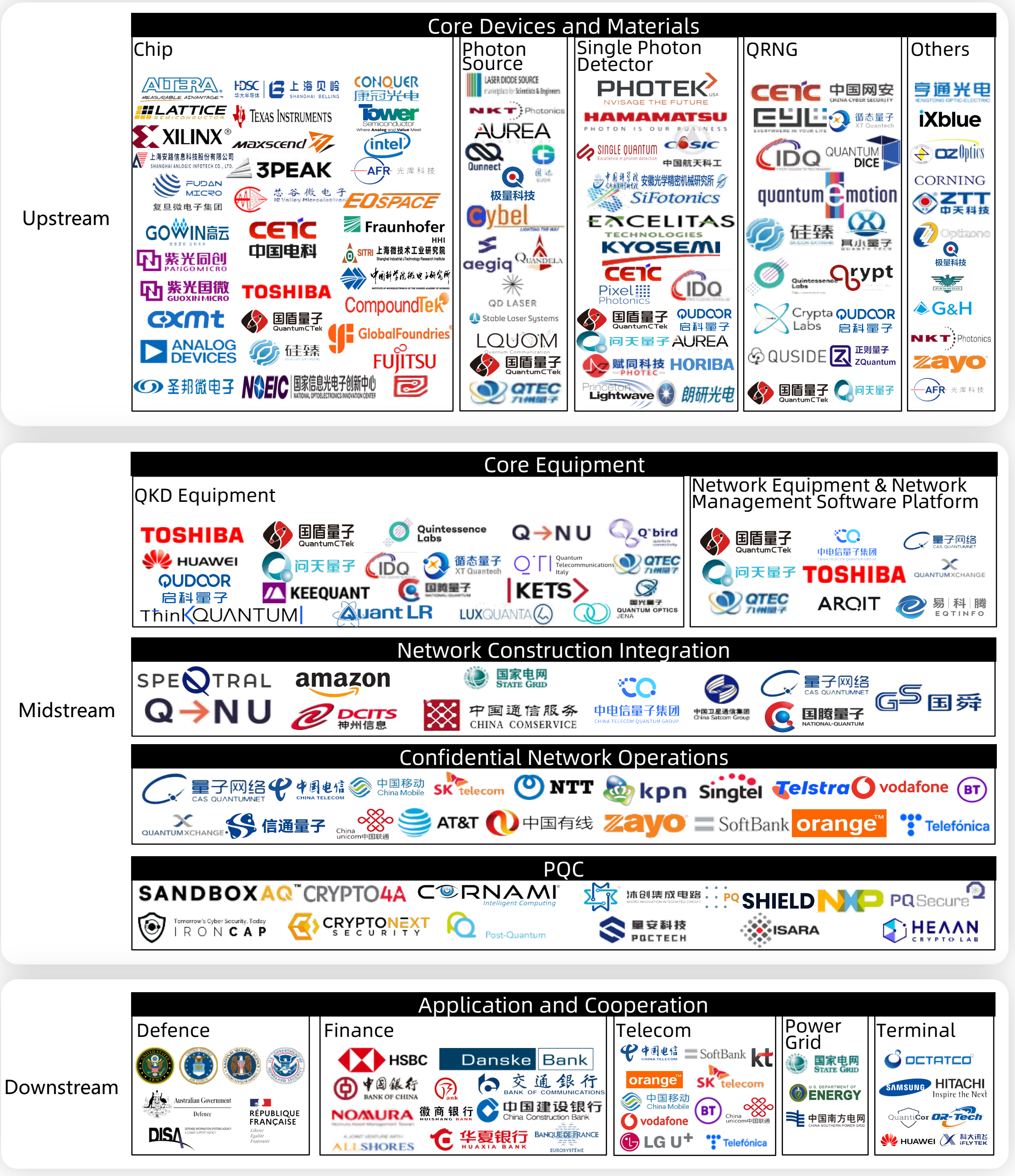
02
Industrial Ecosystem

The development of the quantum communication and security industry chain has reached a relatively mature stage, with a more refined division of labor in the industry chain. As the structure of the industry chain becomes clearer, adjustments have been made to present the current state of the industry ecosystem.

In the upstream of the industry chain, core components and materials are categorized into chips, light sources, single-photon detectors, quantum random number generators, and others. The midstream of the industry chain is divided into the equipment layer, network construction layer, and operation layer. Additionally, this version incorporates PQC into the industrial ecosystem map. The downstream of the industry chain is still categorized based on the main application industries.

Figure: Quantum Communication and Security Industry Ecology Overview



Note: The logo of some companies appears multiple times, intending to demonstrate that the company is involved in various sectors.

01 Upstream of the Quantum Communication and Security Industry Chain

In the upstream of the quantum communication and security industry chain, the coverage of core components and materials includes crucial technological constituents. Foremost is the advanced quantum chip technology, serving as the foundation of the entire industry chain, comprising data processing chips, electronic chips, and optical chips. Light sources become an indispensable key component in quantum communication, acting as carriers that, after modulation of their quantum states, carry quantum information for transmission and sharing between different communication nodes. At the communication receiving end, single-photon detectors play a crucial role in ensuring precise detection of quantum information. The quantum random number generator is a key tool to guarantee the unpredictability of communication. Additionally, other core components such as PPLN (periodically poled lithium niobate) crystals, PPLN waveguides, fiber optic cables, and other elements also play critical roles in the upstream industry chain. These core components and materials provide innovation impetus for the upstream of the quantum communication and security industry chain, laying a solid foundation for achieving more secure and efficient quantum communication systems.

Figure: Quantum Communication and Security Upstream

Technology	Basic Situation	Companies (Partly)
Chip	Data processing chips, such as FPGA (Field-Programmable Gate Array) chips, can be programmed to become devices that implement any desired functionality. Electronic chips are also used in quantum communication, including analog signal processing chips, digital-to-analog and analog-to-digital conversion chips (DAC/ADC), radiofrequency chips, storage chips, and more. Optical chips typically refer to chips that integrate optical functions, such as optical waveguides and optical sensors.	XILINX LATTICE SEMICONDUCTOR ALTERA MEASURABLE ADVANTAGE 国盾量子 QuantumCTek
Photon Source	Photon source is a device or equipment that generates photons and is a fundamental element in implementing quantum physics-based secure communication. Different technological approaches may have varying requirements for photon sources, and lasers are a common type of device used as photon sources.	QD LASER 国盾量子 QuantumCTek aegiq QUANDELA
Single Photon Detector	Single-photon detector can detect the signal intensity of individual photons and convert the optical signal into an amplified electrical signal. In quantum communication, it primarily detects light signals in the visible to near-infrared wavelength range, typically ranging from 400 nanometers to 1310 nanometers. Semiconductor detectors and superconducting detectors are two common types of single-photon detectors.	Princeton Lightwave PHOTEK USA NVISAGE THE FUTURE 国盾量子 QuantumCTek QUDOOR 启科量子
QRNG	Quantum Random Number Generators (QRNG) have evolved into commercial products and serve as a core component in Quantum Key Distribution (QKD) devices. The maturity of these products is continually improving, and from a cost perspective, they have acquired the capability to replace classical random number products.	quantum motion 国盾量子 QuantumCTek QUDOOR 启科量子 IDQ
Other	Crystals: Primarily used for generating and modulating photons used in the transmission of quantum information. Fiber Optic Cables: Fiber optic cables serve as a transmission medium in quantum communication, and low-loss optical fibers effectively enhance the communication distance and speed in quantum communication.	NKT Photonics iXblue 极量科技 亨通光电 HENGTONG OPTIC-ELECTRIC

Note: The industry participants shown in this chart are only a partial representation. For more industry participants, please refer to the quantum communication and security industry chain, as well as the actual situation.

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02 Midstream of the Quantum Communication and Security Industry Chain

In the midstream of the quantum communication and security industry chain, it is divided into core devices, network construction integration, secure network operation, and PQC (Post-Quantum Cryptography). Core devices involve crucial quantum communication equipment, such as Quantum Key Distribution (QKD) devices, networking equipment, and network management software platforms, ensuring the secure transmission of information. Network construction integration is used to build efficient and secure quantum communication networks, such as China's national backbone network, provincial backbone networks, and metropolitan area networks. Secure network operation involves the participation of various operators, driving the daily operation and maintenance of quantum communication technology. Additionally, the midstream of the industry chain has also incorporated the PQC field, including next-generation encryption algorithms, security protocols, chips, etc. This development makes the industry chain more comprehensive, paying closer attention to the evolution of future cryptography. The entire midstream, through the collaborative efforts of devices, network construction, and operation, provides support for the development of quantum communication and security, offering crucial guarantees for achieving more secure and efficient communication.

Figure: Quantum Communication and Security Midstream

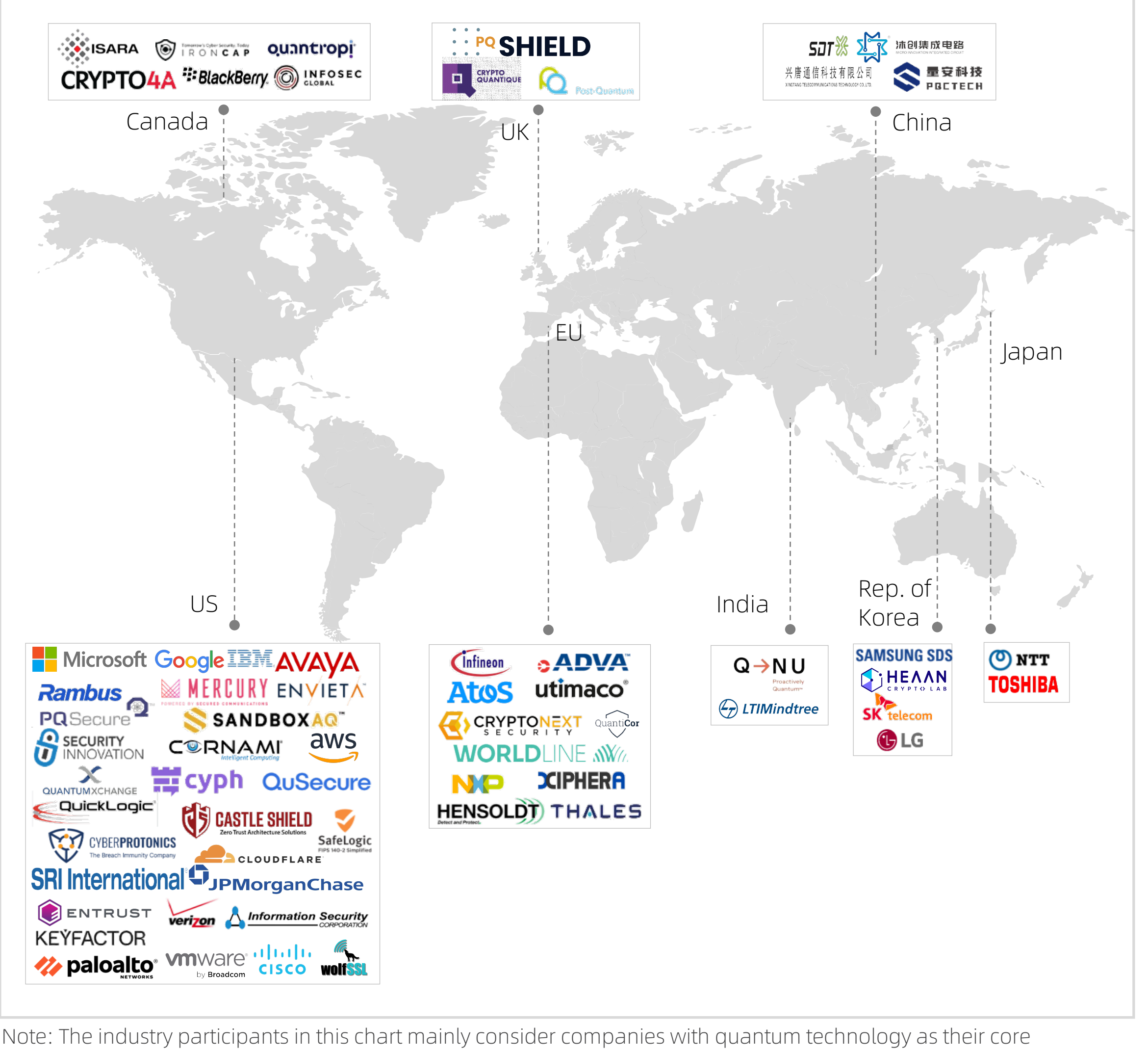
Technology	Basic Situation	Companies (Partly)
Core Equipment	The core equipment primarily consists of Quantum Key Distribution (QKD) devices, networking equipment, and network management software platforms. Commercialized products of QKD devices mainly fall into two categories: Discrete Variable Quantum Key Distribution (DV-QKD) and Continuous Variable Quantum Key Distribution (CV-QKD). Networking equipment and network management software platforms include channel-switching, data processing, and network management software platforms.	TOSHIBA, 国盾量子 QuantumCTek, 问天量子, IDQ, QUDOOR 启科量子, ThinKQUANTUM
Network Construction Integration	The construction of most global Quantum Key Distribution (QKD) networks relies on existing optical fiber communication networks. By selecting suitable locations and deploying QKD transmitters and receivers in data centers, the QKD infrastructure is established.	中电信量子集团 CHINA TELECOM QUANTUM GROUP, SPEQTRAL, 量子网络 QUANTUMNET, QUANTUMXCHANGE
Confidential Network Operations	The operational layer is primarily responsible for managing and coordinating the overall operation of the quantum network. This includes monitoring network status, scheduling the transmission of quantum signals, maintaining network security and stability. At the operational layer, crucial tasks also involve handling key management and distribution, optimizing network resource allocation, as well as fault detection and response.	中国电信 CHINA TELECOM, 中国移动 China Mobile, China unicom 中国联通, SK telecom, orange™, Telstra
PQC	Any new algorithm that can resist quantum computing attacks can be considered as PQC. As a solution based on mathematical algorithms, implemented through chips and accompanying software systems, PQC has advantages in terms of cost and deployment efficiency compared to QKD.	量安科技 PQCTECH, CRYPTO4A, SANDBOXAQ™, PQSHIELD

Note: The industry participants shown in this chart are only a partial representation. For more industry participants, please refer to the quantum communication and security industry chain, as well as the actual situation.

Distribution of Midstream PQC Participants

From the geographical distribution of PQC companies, the United States, the European Union, and China have a relatively dense concentration of companies. Additionally, countries such as Canada, the United Kingdom, Japan, Republic of Korea, and India also have companies participating in PQC research and offering PQC products or services. In terms of business operations, global technology giants like IBM, Microsoft, and Google from the United States have expanded their business into the PQC field. Google, for instance, has applied PQC algorithms to secure its Chrome browser network. India's QNu Labs, referencing NIST's PQC standards, has developed lattice-based PQC algorithms and offers services through its Hodos product.

Figure: Global Distribution of PQC Research Companies



Note: The industry participants in this chart mainly consider companies with quantum technology as their core business. Entry into the quantum field by traditional companies is not included.

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Global PQC (Post-Quantum Cryptography) research institutions are predominantly universities, with a notable presence in China. While many Chinese research institutions are involved in the PQC field, those successfully transitioning to commercialization remain limited. The NIST (National Institute of Standards and Technology) in the United States plays a leading role in PQC standardization. Leveraging this advantage, several research institutions in the U.S. have incubated PQC startups, facilitating their transition into commercial ventures. Additionally, countries such as the European Union, the United Kingdom, Canada, and Japan also host numerous PQC research institutions.

Figure: Global Distribution of PQC Research Institutions

Note: The industry participants in this chart mainly consider companies with quantum technology as their core business. Entry into the quantum field by traditional companies is not included.

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Progress of Global PQC Research Efforts.

The importance of PQC research and application lies in ensuring interoperability and security between different vendors' PQC solutions, promoting the commercialization and widespread adoption of PQC technology, and completing the transition from classical cryptographic systems to PQC. The United States has been the fastest in the standardization process among various countries. Apart from the United States, countries such as the United Kingdom, Germany, France, China, Japan, and Republic of Korea also attach great importance to PQC and have carried out related work in the field.

In terms of international organizations, the Internet Engineering Task Force (IETF) has established the Post-Quantum Cryptography Interest Group (PQUIP) to coordinate the use of encryption protocols. The IETF has approved a new standard for Quantum-Secure Virtual Private Networks (VPNs) proposed and designed by the UK cybersecurity company Post-Quantum. This standard specifies how VPNs can securely exchange communications in the quantum era, prioritizing interoperability and allowing parties using different public key encryption algorithms to communicate with each other, thus enabling the inclusion of various PQC and classical encryption algorithms in VPNs. In September, PQC professionals, researchers, and expert practitioners formed the PQC Coalition to promote the understanding and adoption of PQC standardized algorithms initiated by the United States NIST. Founding members of the coalition include US companies IBM Quantum, Microsoft, MITRE, SandboxAQ, UK-based PQShield, and the University of Waterloo in Canada.

USA

The United States released the "2023 National Cybersecurity Strategy," proposing increased government investment in PQC migration and widespread replacement of hardware, software, and services vulnerable to quantum computing attacks. In August, the United States Cybersecurity and Infrastructure Security Agency (CISA), National Security Agency (NSA), and National Institute of Standards and Technology (NIST) jointly released the "Quantum-Preparedness: Migrating to Post-Quantum Cryptography" guide. In September, the National Cybersecurity Center of Excellence (NCCoE), a division of NIST, released a project description document for the "Migrating to Post-Quantum Cryptography" project, outlining the background, objectives, challenges, benefits, and workflow of the PQC migration project. Additionally, NCCoE listed 28 technology vendors participating in the project, including IBM, Amazon, Microsoft, SandboxAQ, and other leading quantum companies.

China

The China Information Security Standardization Technical Committee convened a seminar on Post-Quantum Cryptography (PQC) technology and innovative practices, discussing topics such as cutting-edge technologies, research dynamics, and development trends in the PQC field, thereby promoting the establishment of PQC standardization and its application implementation.

The Third Yanqi Lake International Seminar on Post-Quantum Cryptography Standardization and Applications, hosted by the Tsinghua University Qiu Chengtong Mathematical Sciences Center and the Beijing Yanqi Lake Institute of Applied Mathematics, was held in Beijing. The seminar focused on discussing international progress in PQC standardization and PQC migration work in various industry sectors.

The establishment ceremony and expert appointment of the Chinese Anti-Quantum Cryptography Strategy and Policy Legal Working Group took place at the main forum of the 13th China Information Security Legal Conference. This working group will conduct research on the current status of anti-quantum cryptography technology, industry, and business, as well as relevant domestic and international policies, laws, and regulations. It aims to publish blueprints, reports, and specialized research on anti-quantum cryptography in public or targeted ways to promote the formation of a consensus and action plan for anti-quantum cryptography in China.

UK

The UK National Cyber Security Centre (NCSC) has released a white paper to assist system and risk owners in commercial enterprises, public sector organizations, and critical national infrastructure providers in preparing for the transition to Post-Quantum Cryptography (PQC).

Germany

The Federal Office for Information Security (BSI) in Germany, in collaboration with Rohde & Schwarz Cybersecurity GmbH, has initiated the "Secure Implementation of a Common Cryptographic Library" project. This project involves the development of the Botan cryptographic library, which by 2023 has advanced to version 3.0.

France

The 9th ETSI/IQC Quantum Safe Cryptography Workshop took place in February 2023 at the ETSI headquarters in France. This meeting brought together talent in quantum cryptography from industry, academia, and government sectors, reaffirming ETSI's commitment to advancing quantum security standardization processes.

Japan

The National Institute of Information and Communications Technology (NICT) in Japan announced a collaboration with Toppan Printing Co., Ltd. to conduct research on Post-Quantum Cryptography (PQC). The two organizations established a PQC-compatible private certificate authority within the Healthcare Long-term Integrity and Confidentiality Protection System (H-LINCOS), an experimental platform operated by NICT. By integrating electronic signature and digital certificate issuance capabilities and coordinating with the "PQC CARD" developed by Toppan Printing and NICT, they aim to validate the effectiveness of tampering detection functionalities.

Republic of Korea

The National Intelligence Service and the Ministry of Science and ICT in Republic of Korea jointly released a comprehensive plan outlining Republic of Korea's transition to Post-Quantum Cryptography (PQC) in the national cryptographic systems by the year 2035. These two organizations, along with the Ministry of National Defense, the Ministry of the Interior and Safety, the Korea Internet & Security Agency, and the Korea Local Information Research & Development Institute, established a working committee and collaborated with the Korea Local Information Research & Development Institute to develop the comprehensive plan. The long-term roadmap spanning over a decade aims to protect Republic of Korea from quantum computing threats and enhance the country's national cybersecurity.

04 Downstream of the Quantum Communication and Security Industry Chain

The downstream of the quantum communication and security industry chain covers a wide range of application areas, including defense, finance, power grids, and terminals. In the defense sector, quantum communication technology is applied to highly confidential military communications to ensure the secure transmission of sensitive information and effectively prevent eavesdropping and cyber attacks. In the financial industry, quantum communication technology facilitates safer and more reliable data transmission, enhancing the protection level for financial transactions and customer information. In the power grid sector, quantum communication can be applied to secure the real-time transmission of data within power systems, preventing network attacks and data tampering to ensure the stability of power grid operations.

- The U.S. Army has awarded QuSecure a Small Business Innovation Research Phase II contract to develop PQC-based encryption technology and solutions for Army users. The contract aims to determine how to implement quantum technology at the tactical edge.
- SandboxAQ has secured a contract from the Defense Information Systems Agency (DISA) to provide an end-to-end PQC management solution.

- HSBC Bank and Quantinuum have signed a series of exploratory projects. The goal of this collaboration is to leverage the power of quantum computing to enhance encryption keys while integrating them with PQC algorithms.
- HSBC Bank used the encryption form of QKD to secure a transaction on its proprietary platform, HSBC AI Markets, exchanging 30 million euros for US dollars.

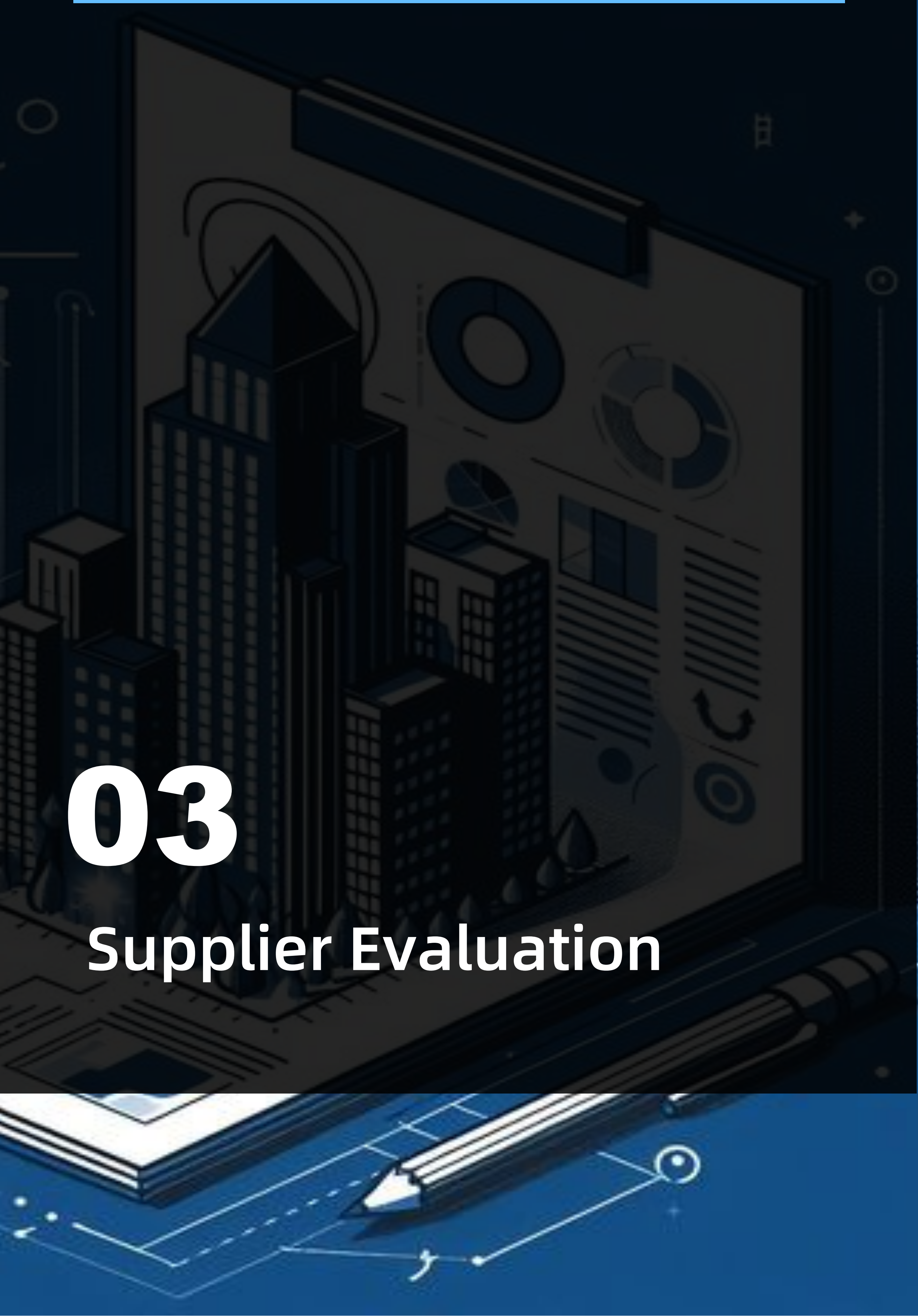
- French company Thales adopts hybrid encryption technology in its mobile security applications and 5G SIM cards, introducing PQC algorithm communication.
- U.S.-based QuSecure launches a real-time end-to-end satellite encryption communication link with quantum resilience.
- Google Chrome introduces a quantum hybrid key exchange mechanism in its latest version (version 116), incorporating the X25519Kyber768 algorithm for quantum-resistant security.
- National Quantum launches a secure email product—National Quantum Secure Email. It utilizes "one-time-one-secret" key distribution technology, combined with high-strength national cryptographic algorithms, to provide users with end-to-end secure email services.

Power Grid

- SGCC Wuhan has implemented quantum encrypted communication in the power distribution automation terminals within the Wuhan Economic Development Zone power supply network. In the newly installed quantum encrypted communication lines, a quantum encrypted communication module was added to each distribution box, enabling quantum encrypted communication by connecting with the power grid communication links.
- The first quantum + substation in Zhejiang Province, the 35 kV Jishan Substation, has been put into operation in the old city area of Shaoxing. The substation underwent a technological transformation with "wireless public network + quantum communication," changing the wired communication of the substation into wireless communication. This transformation connects the existing distribution network quantum switches with the main network quantum + substations for power information data, equipped with a one-key linkage function for the main distribution network. The "Quantum Substation" project was provided with equipment and technical support by Guodun Quantum and its affiliated company Zhejiang Guodun Quantum Power.

Mobile Phone

- China Telecom, in collaboration with Huawei, has released the Mate60 Pro smartphone terminal with customized quantum secure communication capabilities.
- China Telecom and Samsung have introduced two smartphones, Samsung W24 and W24 Flip, featuring quantum secure communication functions in partnership with China Telecom.
- China Telecom has unveiled the Tianyi Platinum 10 and Tianyi Platinum S9 smartphone terminals that support quantum secure communication. The Tianyi Platinum S9 is a 5G satellite dual-mode phone equipped with a TianTong satellite communication chip.
- In cooperation with ID Quantique and Samsung Electronics, SK Telecom has launched the "Galaxy Quantum 4" quantum communication smartphone, featuring a QRNG chip.



03

Supplier Evaluation

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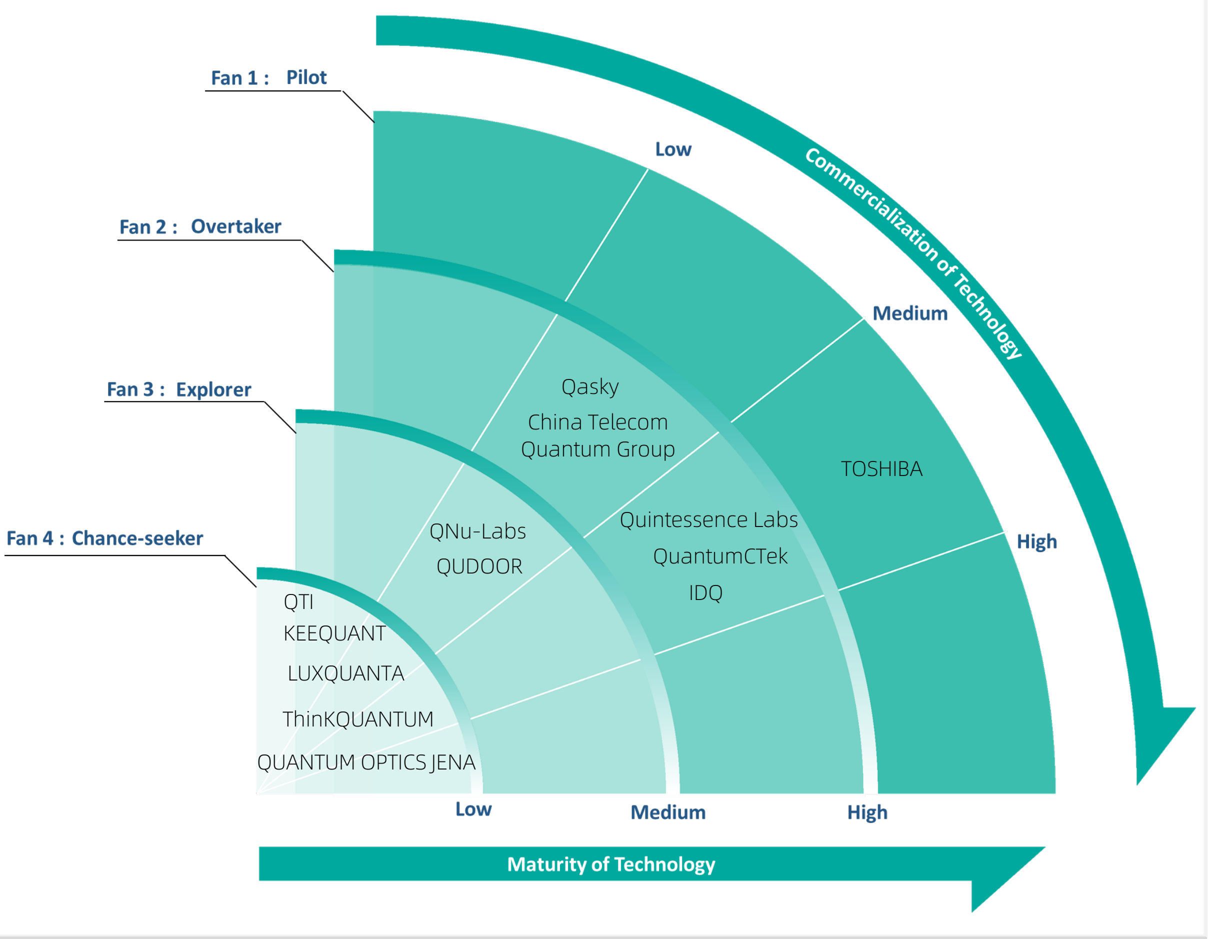
Supplier Evaluation

01 QKD Supplier Analysis

Currently, QKD technology has achieved commercialization of products in the field of quantum communication and security, and it has been widely applied. Therefore, this assessment primarily focuses on suppliers capable of delivering comprehensive QKD system solutions, aiming to provide a comprehensive evaluation of their technological, commercial, and service capabilities.

Figure: Global QKD Supplier Evaluation System

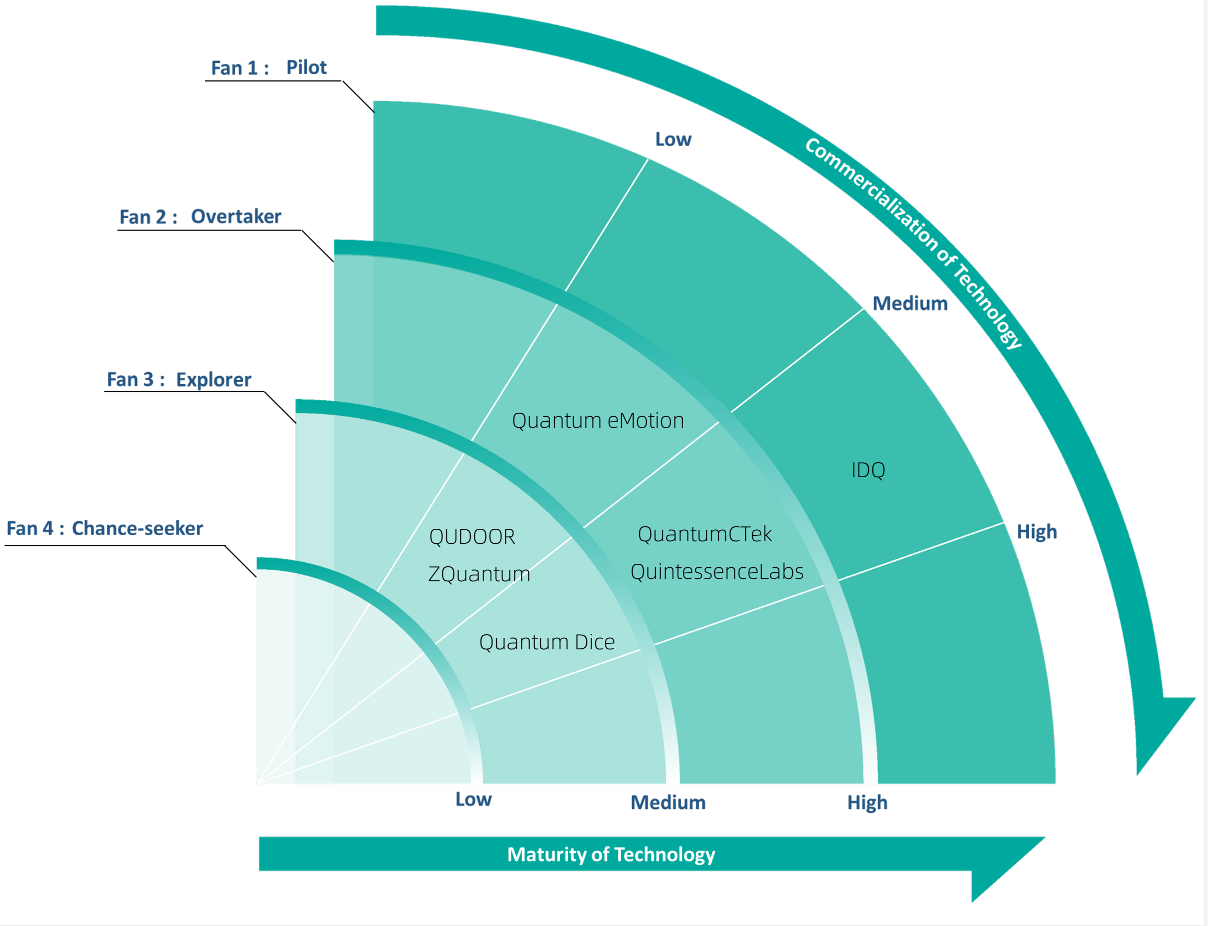


Note: The purpose of the supplier evaluation is to provide information on the current state of the company to the purchasing party and wide-ranging industry participants (such as investment organizations) to aid decision making. The Cutting-edge Tech Fan (CTF) model of future technology evaluation is used to assess suppliers from multiple dimensions including technology (including technology readiness and R&D technology reserves), market (market development and market share), and comprehensive accumulation of the enterprise.

02 QRNG Supplier Analysis

QRNG, by fully leveraging the inherent randomness of quantum mechanics, achieves genuine random number generation, providing a crucial security foundation for quantum communication systems. In quantum communication, the generation of random numbers is paramount for QKD protocols. This true randomness establishes a robust foundation for quantum key generation, guarding against potential eavesdropping and decryption threats. Hence, this assessment will analyze key QRNG suppliers to provide a comprehensive evaluation of their performance in terms of technology, commercial strength, and services.

Figure: Global QRNG Supplier Evaluation System



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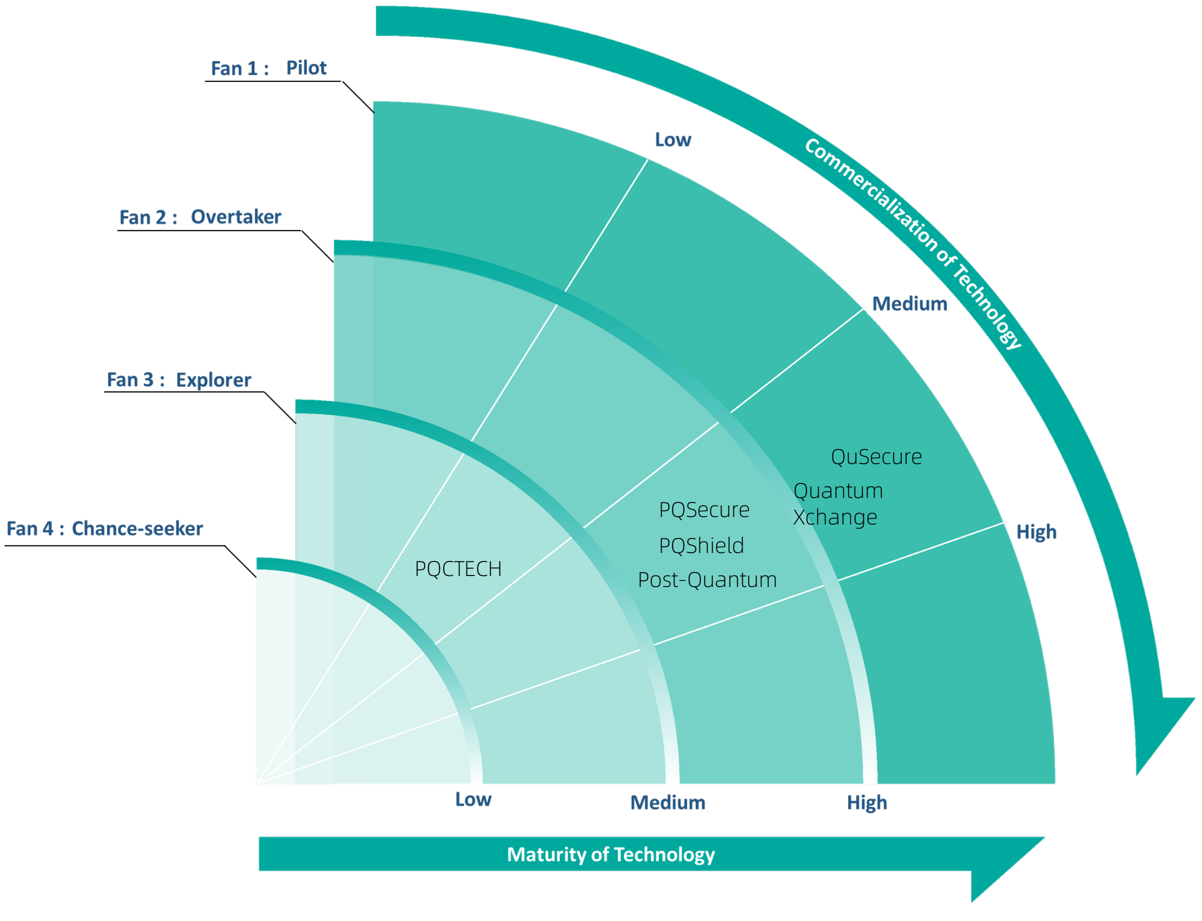
03 PQC Supplier Analysis

Post-Quantum Cryptography (PQC) technology, based on mathematical methods, involves various cryptographic principles and mathematical structures, including lattice-based cryptography, problems in polynomial rings, and hash function design, among others. Through these mathematical methods, PQC technology can achieve secure encryption and signature operations, protecting sensitive information from the threat of "store now, decrypt later." PQC is poised to become one of the future directions in the field of communication security. Therefore, this assessment will comprehensively analyze key suppliers providing PQC solutions or software.

Figure: Global PQC Supplier Evaluation System



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04 Typical Supplier Analysis

Toshiba Europe

In the realm of product research and development, Toshiba established the Toshiba Cambridge Laboratory, where it engineered a gain-switched laser for Quantum Key Distribution (QKD) transmitters. The laboratory calibrated the impact of various intensity seed light injections on its emission power and delay. Collaborating with Orange, Toshiba validated the feasibility of deploying QKD on existing optical fiber networks, highlighting that power (rather than the number of channels) has the most significant impact on efficiency. Partnering with SoftBank, Toshiba successfully conducted a demonstration experiment of QKD-VPN communication based on Internet security protocols (IPsec) by introducing QKD systems and QKD-compatible VPN routers.

In the domain of quantum communication project construction, Toshiba actively participated in the development of Singapore's first nationwide Quantum Security Network (NQSN+) project. The company contributed by providing a suite of products featuring fiber-based QKD and Quantum Key Management System (Q-KMS). Furthermore, on December 19th, Toshiba announced its privatization through a £1.1 billion deal led by the consortium of equity firm Japan Industrial Partners, resulting in its delisting from the Tokyo Stock Exchange.

ID Quantique

Since the launch of its first Quantum Random Number Generator (QRNG) chip in 2020, ID Quantique (IDQ) has expanded the series to six versions, embedding them in various devices such as Samsung smartphones and satellites. At the MWC23 conference, IDQ unveiled a "Quantum Cryptography Single Chip," jointly developed with KCS and SK Telecom (SKT), featuring a QRNG chip and a semiconductor with cryptographic communication capabilities. The DocuSign QSCD device, incorporating IDQ's QRNG chip, obtained FIPS 140-2 Level 3 approval in 2023.

IDQ's QRNG chip serves as a foundation for the "Galaxy Quantum 4" quantum smartphone, a collaborative effort with SK Telecom and Samsung. In the realm of quantum communication infrastructure, IDQ is involved in the EAGLE-1 project, integrating a spaceborne and ground-based Quantum Key Distribution (QKD) system with a near-earth satellite and a ground quantum communication network. Additionally, IDQ partners with Singaporean telecom operator Singtel to provide QKD equipment and Quantum Secure Key Management solutions for Singapore's first nationwide Quantum Security Network (NQSN+). Collaborating with Israeli optical transport company PacketLight, IDQ proposes a solution that combines QKD with network encryption devices, aiming to transform and upgrade existing fiber optic communication infrastructure.

QuantumCTek

As a pioneer in the communication and security industry, QuantumCTek has been at the forefront, primarily focusing on the development of quantum core devices. The company has expanded its involvement into areas such as infrastructure network construction, industry applications, standardization efforts, and popular science education.

In 2023, QuantumCTek achieved notable advancements in various aspects, including products, network construction, technology applications, and industrial ecosystem development. Key accomplishments include: 1. The KunTeng QKD-POL Quantum Key Distribution devices (QKD-POL40A-S, QKD-POL40B-S) from QuantumCTek passed testing at the Commercial Password Testing Center of the National Cryptography Administration. 2. Collaborating with entities such as China Telecom Research Institute and Huawei, the company achieved 1Tbps classical communication data capacity and quantum key distribution services based on few-mode fibers. This accomplishment also involved shared transmission over a hundred-kilometer-level link distance. 3. QuantumCTek provided products and technical support for ensuring communication network security during the Hangzhou Asian Games. 4. Supplying equipment and technology for the Quantum City-Area Network in Hefei. 5. Jointly advancing the development of the "Quantum Security Application Portal Series Products" with DingTalk. 6. Signing an agreement with Hefei University of Technology and jointly releasing the "Typical Application Scenarios of Quantum Communication Systems in the Internet of Vehicles." 7. Participating in and initiating the "Yangtze River Delta G60 Technology Innovation Corridor Quantum Cryptography Application Innovation Alliance (Center)." 8. Receiving recognition as a popular science education base in Hefei. These achievements underscore QuantumCTek's commitment to advancing quantum technologies and their applications across various domains.

SpeQtral

In terms of products, Quantum Dice and Quantum Dice launched the quantum space product Zenith QRNG. This product uses Quantum Dice’s proprietary DISCTM protocol, allowing the product to have a data transmission rate of 200-1000 Mbps. In terms of project construction, we cooperated with Archangel Lightworks to carry out the Quantum Laser Communication Optical Ground Station (QLOGS) project supported by Innovate UK under the UK Department of Research and Innovation and Enterprise Singapore; and jointly constructed Singapore with SPTel National quantum security network project NQSN+.

China Telecom Quantum Group

China Telecom Quantum Group was established in Hefei, Anhui Province in May 2023, with a registered capital of 3 billion yuan. It is a wholly-owned subsidiary of China Telecom Co., Ltd. In terms of key quantum technology research, China Telecom has taken the lead in writing five quantum communication industry standards, and has the core capabilities of quantum encryption with quantum keys and national secret algorithms.

In terms of the transformation of quantum science and technology achievements, the Hefei quantum secure communication metropolitan area network with the largest scale, the most users, and the most comprehensive applications in China has been built; the quantum secret voice and secret message product has been launched, with more than one million online users; the quantum encrypted intercom developed has been Used in the 19th Asian Games in Hangzhou; released the "DICT+Quantum" full-scenario capability system and a series of application products such as call+quantum, network+quantum, cloud+quantum, and platform+quantum.

In terms of promoting the innovative development of the quantum information industry, the Quantum Industry Conference will be jointly held with the Hefei Municipal Government in 2021, 2022, and 2023, which has become a landmark and professional annual event in the industry; China Telecom Quantum Group serves as the main carrier of China Telecom , jointly with leading enterprises in the industry, established the "Quantum Information Application Cooperation Ecological Alliance"; with the theme of "Quantum Technology Points to the Future", the 2023 Quantum Technology China Tour was successfully held in Shanghai, Jiangsu, Zhejiang and other places, and 12 stops were successfully held in Shanghai, Jiangsu, Zhejiang and other places. Quantum technology products were displayed in various forms, and quantum science knowledge lectures were carried out in collaboration with top experts and professors in the quantum industry. A total of more than 30,000 people participated offline, and more than 300,000 people were covered online.

LuxQuanta Technologies

In the realm of products, LuxQuanta unveiled the LuxQuanta® NOVA LQ™ at the 2023 World Mobile Congress. The NOVA LQ™ leverages the advantages of Continuous Variable Quantum Key Distribution (CV-QKD) technology and is designed for deployment in metropolitan area networks without the need for dedicated optical links. In terms of project development, LuxQuanta is actively involved in the Quantum Secure Networks Partnership (QSNP) under the European Quantum Flagship initiative. This new project aims to develop and implement quantum cryptography technologies, advancing the field of quantum-secure communication networks.

Arqit Quantum

In terms of products, Arqit WalletSecure™ and cloud-based symmetric key agreement platform QuantumCloud™ application products will be launched in 2023. Middle East electronic equipment company WLL (AIEE) has signed a QuantumCloud™ license contract; a commercial integration has been launched with BT in the UK and Fortinet in the US. Product for quantum-secure virtual private network (VPN) communications using symmetric key agreement; partnership with Babcock to develop cutting-edge communications and control technology integrating Babcock's SwarmCore technology and Arqit's symmetric key agreement platform in a decentralized manner Receive and transmit data; partnering with DETASAD Saudi Arabia and launching Arqit's sovereign symmetric key agreement platform, and building on this collaboration plans to integrate Arqit technology into DETASAD's MadeinSaudi smart capacity management or any other platform in the DETASAD edge cloud) provides network security.

In terms of business cooperation, Arqit and Exclusive Networks announced the establishment of a distribution partnership for Arqit's symmetric key agreement platform in the United States; a supply partnership with SecureCloud+ in the UK, using Arqit's symmetric key agreement platform and SecureCloud+ services to provide data management and communication services. , devices, sensors and network infrastructure to provide resiliency and protection; establish a strategic partnership with Sierra Nevada Corporation Mission Systems UK (SNC MS UK) to jointly create resilient security solutions and services.

QUDOOR

Qudoor Quantum is a member of the Quantum Information Standards Working Group, a member of the Quantum Technology Industry-University-Research Innovation Alliance, and a founding member of the Quantum Computing Industry Intellectual Property Alliance. It has participated in the formulation of more than 30 national and industry standards in the field of quantum information. In terms of products, its four products (quantum key distribution equipment QCS-288, QCS-289, quantum random number generator QRNG-G1, PCIE-QRNG) have been reviewed by experts and reviewed by the new technology and new product (service) certification team. In the publicity and other aspects, the Beijing New Technology and New Product (Service) Certificate was obtained; the quantum key distribution equipment QCS-289 and the quantum random number generator equipment were certified by the China Academy of Information and Communications Technology and passed the "Quantum Key Distribution (QKD) System Technical Requirements" Part 1: QKD system based on decoy BB84 protocol" and "Quantum Key Distribution (QKD) system test method Part 1: QKD system based on decoy BB84 protocol" standard testing; at the same time, we are also actively promoting quantum + power technology Breakthrough. In terms of corporate cooperation, a strategic cooperation agreement was signed with the Research Institute of China Mobile Communications Co., Ltd. in Zhuhai to carry out in-depth cooperation in multiple fields such as mobile communications and computing power networks.

Quantum Telecommunications

QTI (Quantum Technology Italy) is an Italian quantum communication company specializing in the development and production of Quantum Key Distribution (QKD) systems. It was established in October 2020 and is a derivative company of the National Research Council's National Institute of Optics (CNR-INO) in Italy. QTI offers the Quell-X QKD system, the Key Management Entity QKME, and solutions based on the ETSI GS QKD 015 standard known as QSDN. In August 2021, QTI supported quantum communication infrastructure development between the governments of Italy, Slovenia, and Croatia, conducting the first transmission tests between these three nodes.

CAS Quantum

CAS Quantum, founded in 2016, is equipped with the capabilities for research and development, construction, and operation of facilities and services based on quantum communication technology. These include space-to-ground integrated systems, cloud-network integration, application-driven initiatives, and independently controllable infrastructure. The company is responsible for the "National Wide-Area Quantum Secure Communication Backbone Network," which is fully operational, and it is currently constructing a cloud platform integrating quantum communication technology at the eight major hubs of the national "East Numerical, West Computational" initiative.

In 2023, CAS Quantum has made significant progress in product applications, ecosystem co-building, and demonstration projects. The "Data Encryption Management System Password Module" has been evaluated by the National Cryptography Administration's Commercial Password Testing Center and successfully applied in the production systems of multiple banks. Serving as the leading entity, CAS Quantum, in collaboration with G60 Science and Innovation Corridor, initiated the establishment of the "Yangtze River Delta G60 Science and Innovation Corridor Quantum Cryptography Application Innovation Alliance (Center)," promoting cross-domain integration and interconnection in areas such as government affairs and finance. The company participated in the formulation of the "Hubei Province Accelerated Development of the Quantum Science and Technology Industry Three-Year Action Plan (2023-2025)" and became a key unit in the quantum technology chain. CAS Quantum partnered with the government of Jinhua City to co-establish the "National Quantum Backbone Network Quantum Communication Application Demonstration Center," contributing to the development of Jinhua as a "Quantum City."

QNU Labs

In 2023, QNU Labs collaborated with the Indian Navy for the procurement and deployment of Quantum Key Distribution (QKD) systems. The Indian Navy became the first institution in the country to purchase and deploy a large-scale quantum-based encryption system. Additionally, QNU Labs partnered with Accops to explore advanced solutions in quantum-secure remote access and robust identity authentication.

Quantum Optics Jena

Quantum Optics Jena and Adva Network Security have successfully completed a joint demonstration of entanglement-based Quantum Key Distribution (QKD) technology. This collaboration utilized Quantum Optics Jena's quantum key generation and verification technology, combined with Adva Network Security's Layer 1 encryption solution, to establish an optical communication channel for testing purposes.

ThinkQuantum

In terms of project participation, ThinkQuantum is involved in the European project "Quantum Devices and subsystems for Communications in SpacE (QUDICE)," which aims to develop components and subsystems for quantum communication and optical systems for space-based Quantum Key Distribution (QKD). The primary objective of QUDICE is to enable a European satellite network with quantum key distribution as its main service.

Quantum eMotion

Established in 2017, Quantum eMotion focuses on the upgrade of high-throughput QRNG2 technology. In terms of products, in 2023, they launched the Quantum Security Communication Platform "Sentry-Q," which includes three modules: QRNG2, QXCP, and QGPS. Additionally, they introduced the Quantum Entropy as a Service system "QxEAAS" based on a high-performance quantum random number generator. In terms of business collaboration, they signed a partnership agreement with the healthcare company Greybox Solutions to provide a quantum-secure encryption platform.

04

Infrastructure Development

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Infrastructure Development

01 Construction of QKD Infrastructure Network

In 2023, the development of land-based QKD infrastructure networks progressed further in countries such as the United States, China, Singapore, Canada, France, Ireland, Belgium, and Spain. The developments in each country are as follows:

USA
Conducting quantum network link tests to promote the development of quantum communication.

The Center for Quantum Information Physics (CQIP) at New York University collaborated with the quantum security network technology company Qunnect to successfully test a 10-mile (16-kilometer) quantum network link between the Brooklyn Navy Yard and the Manhattan campus of New York University using Qunnect's quantum security network technology. Through standard telecommunications optical fibers in New York City, Qunnect and CQIP achieved the transmission of highly entangled quantum bits at a rate of 15,000 pairs per second over the 10-mile optical fiber. During the testing process, the link operated normally 99% of the time. This experiment has opened the door for pilot testing of quantum network technology in the financial services, critical infrastructure, and telecommunications companies in the New York metropolitan area.

China
The achievements of the construction of the Yangtze River Delta Quantum Secure Communication Backbone Network were announced, spanning a total length of 2860 kilometers.

The construction achievements of the Yangtze River Delta Quantum Secure Communication Backbone Network, operated and constructed by CAS Quantum Network Co., Ltd, were officially announced at the Fifth Yangtze River Delta Integration Development Forum in June 2023. The quantum network in the Yangtze River Delta region spans approximately 2860 kilometers, with core nodes in Hefei and Shanghai, linking cities such as Nanjing, Hangzhou, Wuxi, Jinhua, and Wuhu to form a ring network. Supported by quantum business operation support systems and quantum satellite scheduling systems, this network provides comprehensive security for space-to-ground integrated quantum secure communication networks.

Singapore
The construction of the first nationwide NQSN+has commenced, aiming to provide commercial data protection.

The construction of Singapore's inaugural National Quantum-Safe Network Plus (NQSN+), supported by the National Research Foundation Singapore, has commenced as a three-year quantum engineering initiative. NQSN+ will initially deploy Quantum Key Distribution (QKD) technology while concurrently exploring Post-Quantum Cryptography (PQC), establishing a hybrid architecture of QKD/PQC, quantum key as a service, and service-oriented QKD networks. This transformation aims to evolve from a point-to-point to a multipoint interconnected network, culminating in an interoperable network endowed with quantum encryption capabilities. In November, the Infocomm Media Development Authority of Singapore appointed local digital service provider SPTel and Singaporean quantum communication firm SpeQtral to jointly undertake the construction of the NQSN+ project. SpeQtral has announced enhanced collaboration with Japan's Toshiba in quantum communication, leveraging Toshiba's fiber-based QKD and quantum key management system product suite to support the construction of NQSN+. Companies such as ID Quantique, EvolutionQ, Thales, among others, will also be involved in this project's development.

Canada
They increase investment to construct the foundational infrastructure for a nationwide quantum communication network is crucial for laying the groundwork for future advancements.

The Canadian government and the government of Quebec have respectively allocated $3.6 million CAD and $4 million CAD to construct Canada's first quantum communication test platform. This project serves as essential infrastructure for testing quantum communication technology and has the potential to become the cornerstone of Canada's future quantum communication network. Currently, the first node of this test platform has been constructed in the city of Sherbrooke, Canada.

EU
The EuroQCI project is progressively advancing, with plans for operational deployment anticipated by 2027.

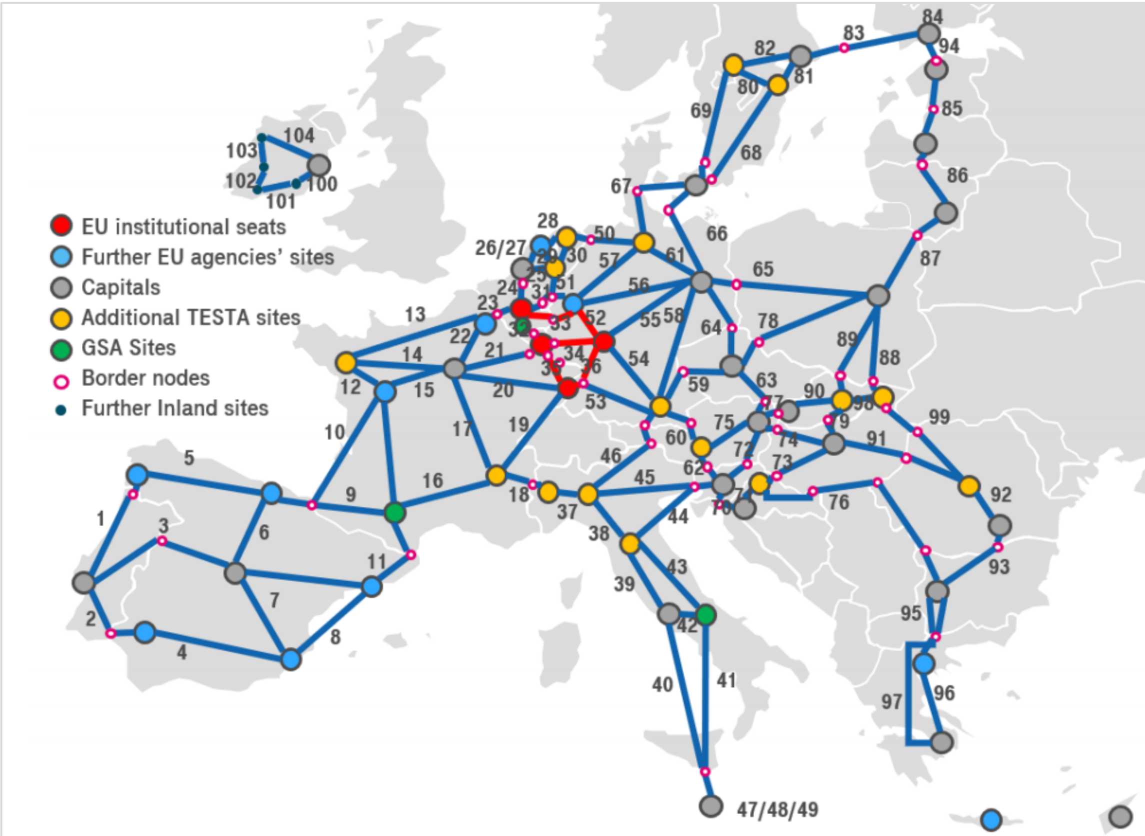
The European Quantum Communication Infrastructure (EuroQCI) is a quantum communication security infrastructure covering the entire European Union and its overseas territories. The European Commission collaborates with all 27 EU member states and the European Space Agency (ESA) to design, develop, and deploy EuroQCI, which consists of both ground-based and space-based components. The ground-based segment relies on fiber optic communication networks connecting national and cross-border strategic sites, while the space-based segment is constructed using satellites. EuroQCI was initiated with the EuroQCI Declaration in June 2019, initially signed by seven member states (Belgium, Germany, Italy, Luxembourg, Malta, the Netherlands, and Spain). In July 2021, with the accession of the 27th member state, Ireland, all member states joined the initiative.

The terrestrial portion of the EuroQCI project is implemented by EU member states, while the space segment is overseen by ESA. The first implementation phase of EuroQCI began in January 2023, with the project expected to last for 30 months, concluding in June 2025. The ground-based portion of EuroQCI focuses on the following areas:

- A series of industrial projects aimed at developing key technological building blocks for EuroQCI with the goal of advancing Europe's quantum communication ecosystem and industry.
- National projects allow member states to design and build national quantum communication networks, which will form the foundation of the ground-based segment. These networks will adapt to each country's specific requirements by testing different technologies and protocols.
- As the central coordinator among all projects, PETRUS is responsible for facilitating coordination and providing support, while also establishing standardization requirements.

The space segment of EuroQCI primarily involves collaboration between the European Commission and the European Space Agency (ESA). Building upon the existing prototype satellite, Eagle-1, the EuroQCI's first-generation satellite constellation specifications are being developed. The launch of this satellite is anticipated by late 2025 or early 2026.

Figure: Potential Sites for the Ground Segment of the EU EuroQCI Project



Origin: Jean-François Buggenhout "EU Quantum Technologies Flagship and the quantum internet" ENISA TELECOM SECURITY FORUM, 29 June 2022

The planning and construction of the EuroQCI project cover several key aspects, as indicated by publicly available information from participating countries. The project construction primarily revolves around four main areas:

Firstly, Strategic Level: Building European Technological Sovereignty - This involves laying the groundwork for future technological developments to secure Europe's position in the quantum field. Through the project, European countries aim to establish independent control over quantum communication technology, ensuring competitiveness in this domain.

Secondly, Infrastructure Development: This includes the construction of ground-based Quantum Key Distribution (QKD) networks in each country, with some countries also involved in space-based QKD network construction and the establishment of cross-border connections.

Thirdly, demonstrating use cases, fostering industrial ecosystem development, and standardization efforts are integral components of the EuroQCI project. By showcasing the effectiveness of quantum communication technology in practical applications, the initiative aims to propel the development of the industry chain. Simultaneously, the establishment of standards will ensure consistency and comparability across the entire European quantum communication ecosystem, facilitating widespread technological adoption.

Fourthly, on the training front, the EuroQCI project aims to provide technical education to government officials, stakeholders, and other relevant parties, along with educating students and disseminating knowledge of quantum technology to the public. This training encompasses not only the education of professionals in the field of quantum technology but also the cultivation of policymakers and decision-makers. Additionally, the project places emphasis on educating students to nurture the next generation of professionals in the field of quantum communication.

Figure: EuroQCI Project Status

No.	Country	Project	Construction Content
1	Belgium	BeQCI	Infrastructure Content: Implementing multiple quantum links along dedicated optical fibers at various nodes across the country (including Brussels, Leuven, Ghent, Hasselt, and Leuven) and diverse topologies, utilizing different QKD systems. Exploring potential interfaces with space quantum communication networks and the possibility of establishing (long-distance) QCI links with neighboring member states Luxembourg and the Netherlands. Achieving Three Main Objectives: Ensuring the security of the entire communication chain, reducing the cost of QKD systems, and increasing the length of quantum links. On the hardware front, the goal is to develop and integrate receivers (for CV-QKD), chip-level transmitters (for MDI-QKD), and frequency converters (for connecting with solid-state quantum states in diamonds) among other components. On the software front, the objective is to design novel QKD protocols for authentication and classical (post-quantum) encryption protocols, along with enhancing security analyses. Training and Dissemination: Providing QKD education to potential users in administrative, industrial, and governmental sectors. Educating students in quantum technologies, including QKD. Conducting outreach activities to introduce the wonders of the quantum world to the general public.
2	Bulgaria	BG QCI	The coordinating entity is the National Quantum Communication Center (QUASAR), which is part of the Institute of Robotics at the Bulgarian Academy of Sciences. Infrastructure Content: Constructing two pilot quantum links. The first link is located within the city limits of Sofia and will encompass information arrays of the Ministry of Interior, Ministry of Defense, and Ministry of Transport. The second link, spanning 280 kilometers, extends the quantum network to the Kulata border crossing, connecting Sofia with Greece.

No.	Country	Project	Construction Content
3	Croatia	CroQCI	Establishing a ground-based QKD network based on optical fibers; preparing to connect quantum communication infrastructure with neighboring EU member states.
4	Cyprus	CYQCI	The planned quantum communication network spans three cities in Cyprus, utilizing the existing optical communication infrastructure. It will deploy at least 6 use cases and serve 11 end-users to protect public organizations, critical infrastructure, academic institutions, and industrial services. Additionally, optical ground stations will communicate with near-Earth orbit satellites, connecting Cyprus with other EU countries. Finally, the establishment of a Quantum Communication Capability Center is planned to provide research, education, and training programs.
5	Czech Republic	CZQCI	The infrastructure development for the quantum communication network includes: (1) Building the first long-distance quantum communication network connecting backbone cities such as Prague, Brno, and Ostrava. (2) Connecting public institutions and testing use cases and scenarios in metropolitan branches. (3) Providing laboratories with various representative QKD technologies for testing and researching infrastructure technology.
6	Estonia	EstQCI	(1) Establish the relevant knowledge and capabilities for future QKD network and service deployments. (2) Test the quantum communication infrastructure equipment in the 27 EU countries to assess suitability for Estonia's conditions and requirements. (3) Conduct network tests between long-distance quantum networks. (4) Collaborate with neighboring countries to prepare for cross-border connections with Finland, Latvia, and Sweden.
7	Spain	EuroQCI-SPAIN	(1) Design the preliminary national architecture for EuroQCI in Spain, starting from the major cities of Madrid (MAD) and Barcelona (BCN) and gradually expanding to more locations. Deploy QKD encryption systems and demonstrate the functionality of the QKD systems on-site at the Madrid and Barcelona nodes. (2) Provide quantum networks to public institutions, showcase use cases, and develop a national quantum communication ecosystem, with future expansion into the private sector. (3) Evaluate the feasibility of free-space and long-distance quantum communication networks compatible with the EuroQCI architecture, both intra-city and inter-city, including trusted node and quantum relay demonstrator deployments. Investigate the interfaces between QCI space and ground segments.
8	France	FranceQCI	Ground Segment: Utilize the existing infrastructure in Paris (ParisRegionQCI) and Nice (Quantum@UCA/Nice) regions to advance the operation of QKD services. Space Segment: Implement the quantum network in Toulouse (DGAC/DSNA/DTI Laboratory) to test real end-user services for the French Civil Aviation Authority, including the exchange of simulated air traffic control data protected by QKD.

No.	Country	Project	Construction Content
9	Greece	HellasQCI	Utilizing QKD, ground fiber optics, and satellite technology to connect strategic locations in Greece (Athens, Thessaloniki, Heraklion, and Crete Island) with three optical ground stations (Chelmos, Holomontas, and Skinka).
10	Ireland	IrelandQCI	(1) Establish QKD infrastructure along the main network backbone from Dublin through Waterford to Cork, using dark fiber integrated with existing classical fiber optic systems. Additionally, include two city networks connecting public, industry, and academic organizations. (2) Collaborate with key stakeholders to test 16 advanced use cases of quantum-safe technologies, collecting service requirements to support over 40 Irish use cases. (3) Build an innovative quantum technology ecosystem, including establishing testing and engineering facilities for the public, industry, and academia, developing and testing equipment in quantum networks, and connecting with the European Integrated Photonics Experimentation Line. (4) Provide quantum communication education for key stakeholders and the public, fostering a quantum-ready workforce.
11	Latvia	LATQN	Develop a national experimental QKD network and integrate it with the existing communication networks of project partners. The experimental QKD network will consist of infrastructure QKD backbones (public and closed sections), incorporating integrated quantum encryption solutions.
12	Luxembourg	Lux4QCI	Design, develop, procure, and deploy the first experimental quantum communication infrastructure network, focusing on government communication and secure data center connectivity.
13	Finland	NaQCI.fi	Test QKD technology for urban and long-distance links in Finland; deploy cross-border links with neighboring countries Estonia and Sweden, as well as potential future satellite links.
14	Sweden	NQCIS	Deploy and test QKD systems tailored to Sweden's specific requirements, explore various implementation scenarios, and determine the most effective solutions for secure communication. This includes implementing solutions suitable for Sweden's geographic features, such as urban networks, long-distance networks, ground-to-satellite links, and undersea links.
15	Poland	PIONIER-Q	Develop and integrate quantum communication network infrastructure with existing optical and data transmission technologies; deploy national, backbone, and metropolitan quantum networks; collaborate with public users to deploy and test use cases; provide a quantum training environment.

No.	Country	Project	Construction Content
16	Malta	PRISM	Establish a network comprising approximately 20 links on the Melita fiber network spanning Malta and connect it directly to Sicily through the Melita submarine cable. In the second phase of the EU-wide plan launched in 2025, the Maltese network will link to similar quantum networks in neighboring EU countries. The third phase involves deploying quantum satellites covering all EU member states.
17	Portugal	PTQCI	Deploy an elastic network within the existing fiber infrastructure, connecting various public institutions in Lisbon, along with a test network involving academic and private stakeholders. Prepare to extend the network to more distant regions in Portugal and assess the infrastructure for the ground-to-space segment.
18	Germany	Q-net-Q	Provide a long-distance QKD link between Berlin and Frankfurt, implementing point-to-point QKD connections through trusted relay configurations. QKD keys generated by each individual link are combined in an encrypted manner at the key management system layer, generating the final key between remote endpoints in Berlin and Frankfurt. QKD nodes will be installed at secure locations along the fiber optic route, approximately 80 kilometers apart.
19	Austria	QCI-CAT	Deploy QKD testing facilities using the existing fiber optic infrastructure in Vienna and Graz. Combine state-of-the-art modern encryption technologies, such as Post-Quantum Cryptography (PQC), with QKD protocols in a way that is easy to adapt and implement. This integration aims to protect sensitive information dissemination between various institutions, hospitals, and universities in Austria. Implement top-level security features, including trusted nodes, along the link between Graz and Vienna, and test quantum relays.
20	Denmark	QCI.DK	Establish a quantum-secure network between five Danish public institutions and two related data centers in the Copenhagen area. This infrastructure also includes a 200 km long-distance link, connecting three collaborating partner universities through a metropolitan network. Additionally, three different Quantum Key Distribution (QKD) technologies will be combined in one network for testing and applications.
21	Hungary	QCIHungary	Connect the capital Budapest with three different cities in different directions (Győr, Nagykanizsa, Szeged). Future plans include cross-border connections with Austria, Slovakia, Slovenia, Croatia, and Romania. Develop continuous variable and fiber-based entangled Quantum Key Distribution (QKD) systems based on existing research. In addition to ground-based fiber QKD systems, there are plans to prepare for future satellite-based QKD links by developing free-space quantum links and installing ground stations with quantum capabilities.

No.	Country	Project	Construction Content
22	Netherlands	QCINed	Deploy quantum systems and networks to test quantum communication technologies and integrate them with existing communication networks. Implement three distinct advanced experimental Quantum Key Distribution (QKD) networks in three regions: Utrecht Region, Amsterdam-The Hague Region, and Eindhoven Region.
23	Italy	QUID	Develop nodes in the Metropolitan Quantum Communication Network (QMAN) and interconnect them through the Italian Quantum Backbone Network. This infrastructure will use commercial optical fibers to distribute time and frequency standard signals, covering the territory of Italy. Additionally, it will connect key sites to bridge optical communication with the spatial part of the European Quantum Communication Infrastructure (QCI). Develop higher key-rate QKD technologies and novel optical fibers.
24	Romania	RoNaQCI	Deploy a QCI network spanning over 1500 kilometers, including urban networks in cities such as Bucharest, Iasi, Cluj-Napoca, Timisoara, Craiova, and Constanta. This network will consist of 36 QKD links crossing Romania, connecting 10 universities, 5 research institutions, 5 public organizations, and 3 national and regional entities.
25	Slovenia	SiQUID	Establish QKD links between nodes and test quantum networks at research institutions in Ljubljana based on entanglement distribution protocols to implement quantum communication protocols. Additionally, advanced quantum communication protocols such as device-independent QKD and remote entanglement will be tested to further enhance the security of QKD implementations.
26	Slovakia	skQCI	Implement various entanglement-based QKD protocols using the same hardware and technology. This will be done in the first phase to populate 6-12 nodes across Slovakia, creating a national quantum network.

The following are the latest developments in the construction of quantum communication infrastructure in some participating countries of the EuroQCI project. Due to differences in planning, design, construction goals, and timelines among countries, the progress of construction varies.

Latvia
Integrating quantum communication infrastructure to connect key collaborative institutions.

The Latvian National Broadcasting and Television Center is collaborating with the Internet service provider Tet, the Latvian Electronic Communications Office, and the Institute of Mathematics and Computer Science at the University of Latvia to establish a national quantum communication infrastructure system and network, starting in October. The project aims to create an efficient quantum key distribution network among the three partners, utilizing these technologies and their integration into existing infrastructure, while also upgrading skills and developing new services.

France
Initiating a quantum communication infrastructure project to safeguard user data.

In April, France initiated the FranceQCI project to test quantum communication technology and integrate it into the existing communication networks of France. Leveraging existing infrastructure in the Paris and Nice regions, the project advances the operation of Quantum Key Distribution (QKD) services. A quantum network will also be implemented in Toulouse to test real end-user services for the French Civil Aviation Authority, including the exchange of simulated air traffic control data protected by QKD. The project is jointly promoted by entities such as Airbus, CNRS, Cryptonext Security, Direction Générale de l'Aviation Civile, Orange, Université Sorbonne, Paris Telecom, Thales, Thales Alenia Space, University of Côte d'Azur, Veriqloud, and Welinq.

Denmark
Initiating a quantum communication infrastructure project to test various QKD technologies.

In March, Denmark officially launched the construction of its quantum communication infrastructure project (QCI.DK). This project aims to establish a quantum-secure network between five Danish public institutions and two related data centers in the Copenhagen area. Additionally, the infrastructure includes a 200-kilometer long-haul link connecting three participating university partners via metropolitan networks. QCI.DK will integrate three different QKD technologies within a single network, enabling extensive testing and applications.

Ireland
Embarking on the construction of quantum communication infrastructure to upgrade existing networks.

The Ireland Quantum Communication Infrastructure plan (IrelandQCI) aims to establish a quantum technology ecosystem, where researchers collaborate to integrate quantum devices and systems into Ireland's communication infrastructure. The IrelandQCI team is establishing Quantum Key Distribution (QKD) infrastructure along the main network backbone from Dublin via Waterford to Cork, utilizing quantum channels integrated with existing classical fiber optic systems.

Belgium
Introducing quantum communication and deploying quantum communication networks.

The Belgium Quantum Communication Infrastructure (BeQCI) project was launched in January 2023. It aims to establish multiple quantum links along dedicated optical fibers between various nodes across Belgium, including the Brussels region, Leuven, Ghent, Hasselt, and Redu, using different topologies and selecting various Quantum Key Distribution (QKD) systems. Additionally, BeQCI will explore potential interfaces with space-based quantum communication networks and the possibility of (long-distance) QCI links with neighboring countries such as Luxembourg and the Netherlands.

Bulgaria
Constructing the first quantum communication infrastructure to safeguard sensitive data and critical infrastructure.

The construction of Bulgaria's first quantum communication network officially commenced in February. The infrastructure development will be coordinated by the National Quantum Communication Center, QUASAR, which is a part of the Bulgarian Academy of Sciences' Institute of Robotics. Over the next thirty months, experts from this center will build two pilot quantum links. One of these will be located within the city of Sofia and will encompass arrays of information from the Ministry of the Interior, Ministry of Defense, and Ministry of Transport. The second route will be a 280-kilometer-long line, extending the quantum network to the transit point at Kulata, connecting Sofia with Greece.

02 Satellite Communication Infrastructure Development

In 2023, there were further developments in satellite communication construction in countries such as the United States, China, Singapore, and Canada. The specific developments are as follows:

USA
Embedding PQC technology ensures the security of satellite communication.

QuSecure has launched the first real-time end-to-end satellite encryption communication link with quantum resilience. This milestone signifies the first usage of Post-Quantum Cryptography (PQC) in US satellite data transmission to resist both classical and quantum decryption attacks, ensuring the security of satellite data communication. QuSecure's quantum-resilient encryption communication link enables any federal government and commercial organization to conduct real-time, secure, classical, and quantum-safe communication and data transmission through space. In a secure satellite communication test on the Starlink network, QuSecure successfully transmitted quantum-resilient data from Quark servers through Rearden Logic's laboratory in Colorado to Starlink terminals. The signal was then sent to Starlink satellites via the uplink and transmitted back to Earth via the downlink. All of this communication was protected by QuSecure's Quantum Secure Layer (QSL), ensuring the security of all data transmission through PQC network security protection.

In the same month, QuSecure announced a partnership with Accenture in Ireland to develop and test PQC-protected multi-orbit quantum-resilient satellite communication capabilities, effectively combining the advantages of low Earth orbit satellites and geostationary equatorial orbit satellites to achieve data transmission between space and Earth.

US nanosatellite service provider Sky and Space (SAS) announced a partnership with CyberProtonics. CyberProtonics will embed PQC technology into SAS's nanosatellites and ground terminal clusters in preparation for the launch in early 2024. This collaboration will ensure the security of satellite communication, providing stronger data protection for future satellite networks.

China
Establishing a wide-area quantum communication network combining high and low Earth orbit satellites.

Chinese Academy of Sciences scientist and the 14th National Committee of the Chinese People's Political Consultative Conference (CPPCC) member Pan Jianwei, stated in a media interview: "We are collaborating with the National Space Science Center to develop a medium-to-high Earth orbit satellite. In the future, by combining high orbit satellites with low Earth orbit satellites, we will construct a wide-area quantum communication network. This network will include 3-5 small satellites dedicated to Quantum Key Distribution (QKD), generating entangled particles for use as quantum keys, with a mass below 100 kilograms. Low Earth orbit satellites will provide connections between cities, while satellites in higher orbits will allow the creation of a global, 24/7 quantum communication network. This network will use elements of quantum mechanics to encrypt and securely transmit information." China has also been constructing ground stations for this network, and currently, demonstrations of quantum communication between the "Micius" satellite and cities such as Beijing, Jinan, Weihai, Lijiang, and Mohe have been achieved.

Singapore
Building QKD satellites to create future commercial QKD services.

Singaporean quantum communication company SpeQtral has announced a partnership with NanoAvionics, a nanosatellite manufacturer, and satellite photonics company Mbryonics to build the SpeQtral-1 satellite. SpeQtral-1, the second QKD satellite of the SpeQtral project, will serve as a commercial pathfinder to define future QKD services. This mission will also be part of the INT-UQKD program by the European Space Agency, in collaboration with the SpeQtre project, to explore international use cases for QKD.

Canada
Preparing satellite mission architecture and lay out quantum communication network.

HyperSpace is a collaborative project initiated by Canada and Europe, spanning a duration of three years. The primary objective of this collaboration is to demonstrate the feasibility of a transatlantic quantum satellite link. This link aims to distribute entangled photons between quantum ground stations in Canada and Europe using various methods. The team will focus on integrating quantum photonics and optical space communication, exploring innovative protocols and quantum link technologies. One of the use cases for the HyperSpace satellite is to establish an encrypted link between two quantum ground stations using Quantum Key Distribution (QKD).

India
Completing the quantum communication link demonstration experiment paves the way for satellite-based quantum communication.

The Raman Research Institute (RRI) has discovered a secure quantum communication link that will aid India in designing and developing secure communication channels, especially for defense and strategic purposes. RRI successfully established secure communication using Quantum Key Distribution (QKD) between a fixed source and a mobile receiver, paving the way for future ground-to-satellite secure quantum communication. This marks the first such demonstration in India, as stated by the institute. This research is part of the Quantum Experiments using Satellite Technology (QuEST) project, and since 2017, RRI has been collaborating with the UR Rao Satellite Centre of the Indian Space Research Organisation (ISRO).

Israel
Launching the first nanosatellite marks a significant step forward in the field of quantum communication.

The nanosatellite TAU-SAT3 was launched into space from the Cape Canaveral Space Force Station in Florida aboard a SpaceX Falcon 9 rocket. Developed by researchers from Tel Aviv University (TAU) in Israel, the TAU-SAT3 satellite is expected to orbit the Earth at an altitude of 550 kilometers for approximately five years, conducting various scientific missions. TAU-SAT3 is a 20-centimeter nanosatellite and is Israel's first satellite built for advancing research in space optics and quantum communication.

05

Investment & Financing

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Investment and Financing

Currently, quantum communication and security remain futuristic technologies, and this chapter primarily focuses on the startups established as a result. Many traditional networking and information security companies have ventured into quantum communication and security research or business activities. However, these companies, having accumulated capital through long-term operations, rarely require injections of venture capital. Quantum startups, especially those primarily focused on hardware development, typically have minimal collateral in the early stages and face risks in research and development. Therefore, it is uncommon for them to obtain bank loans, and they primarily rely on risk capital and government funding to support their initial development.

In terms of statistical amounts, besides funds from venture capital firms (this chapter does not delve into whether venture capital is part of government-industry guidance funds), startups also receive investments from government-sponsored projects (for example, funding/grants from UKRI in the UK). Both of these sources of funding may coexist in a single round of funding for a company, making it challenging to separate them in detail. Therefore, investments from venture capital firms and funds directly invested by governments into companies are both included in this calculation. The financing data in this study is derived from publicly available information, and investments from companies that have not disclosed their investment situation or the amount of investment are not included in the calculation. Some companies' technologies and businesses not only involve quantum communication and security but also may include quantum computing or quantum precision measurement. Publicly disclosed investment amounts often do not specify the exact direction of research and development. The currency of the funds is mainly in US dollars, with some in euros, pounds sterling, Australian dollars, Chinese yuan, Republic of Korean won, and Indian rupees. The calculated amount does not consider inflation or exchange rate fluctuations.

In summary, there may be deviations in the actual investment amounts received by companies in the quantum communication and security sector. Therefore, the above circumstances need to be considered when using the data.

The main characteristics of financing in 2023 are as follows:

Overall financing overview: Financing in the field of quantum communication and security in 2023 saw a significant decrease compared to 2022.

Regional distribution of financing: The majority of funds were directed towards companies in the United Kingdom, followed by the United States and France.

Types of financing: The primary types of financing were Series A rounds and other strategic investments, with no investments occurring beyond Series B rounds.

Industry financing: The financing amounts across industries showed relatively minor discrepancies.

Financing frequency: The number of financing rounds has been decreasing annually since 2021.

01 Overall Overview of Financing

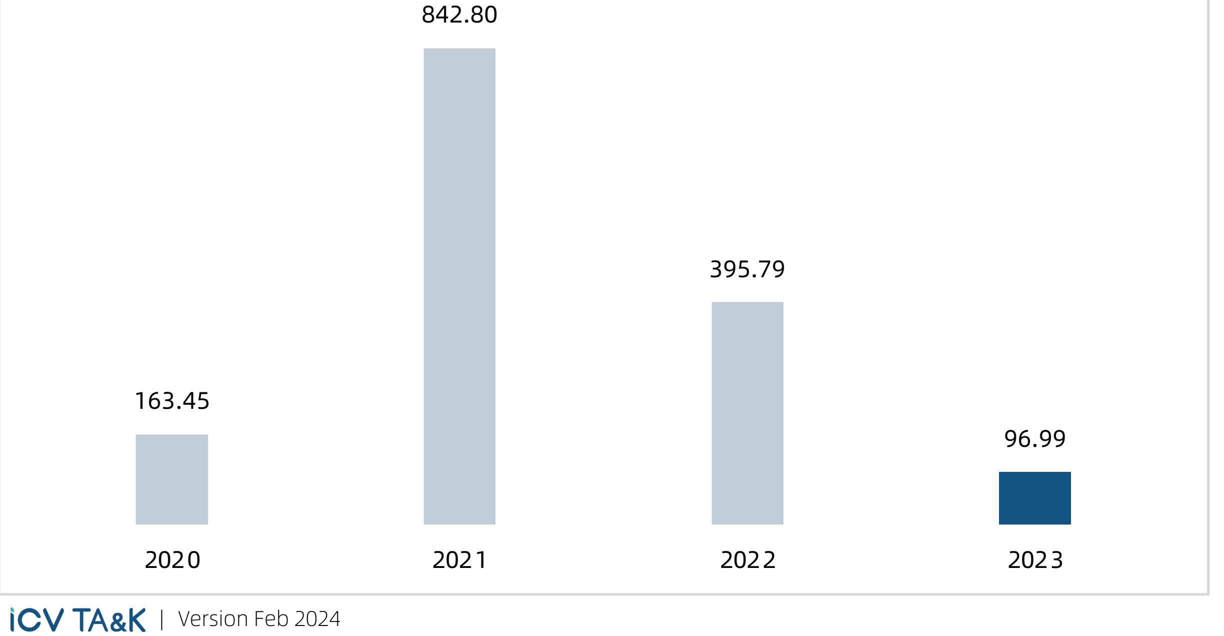
In 2023, financing in the field of quantum communication and security saw a significant decrease compared to 2022.

In 2023, a total of 14 companies in the field of quantum communication and security received approximately $96.9896 million in financing, with approximately 36% of the companies not disclosing their financing amounts. This statistical analysis included estimated funding amounts ranging from $0 to $20 million for companies such as Aliro Quantum in the United States, Crypto Quantique in the United Kingdom, Quside in Spain, Quantum Technology in China, and Terra Quantum in Switzerland.

It is worth noting that Sandbox AQ, a company based in the United States, is involved in multiple areas including security suites, quantum sensing, quantum computing, and quantum communication. In February 2023, they disclosed a $500 million financing round without specifying its purpose. Therefore, this financing is categorized as part of the quantum computing field, and the statistical analysis for quantum communication and security did not include Sandbox AQ.

Compared to 2022 (approximately $396 million), the total financing amount in 2023 decreased. The instability of the global economic situation and potential policy and regulatory changes may have caused investors to adopt a conservative attitude towards investments in emerging technology fields, thereby affecting the scale of investment and financing. Additionally, the data collection process is based on company announcements, which may result in delays compared to the actual financing events of the companies.

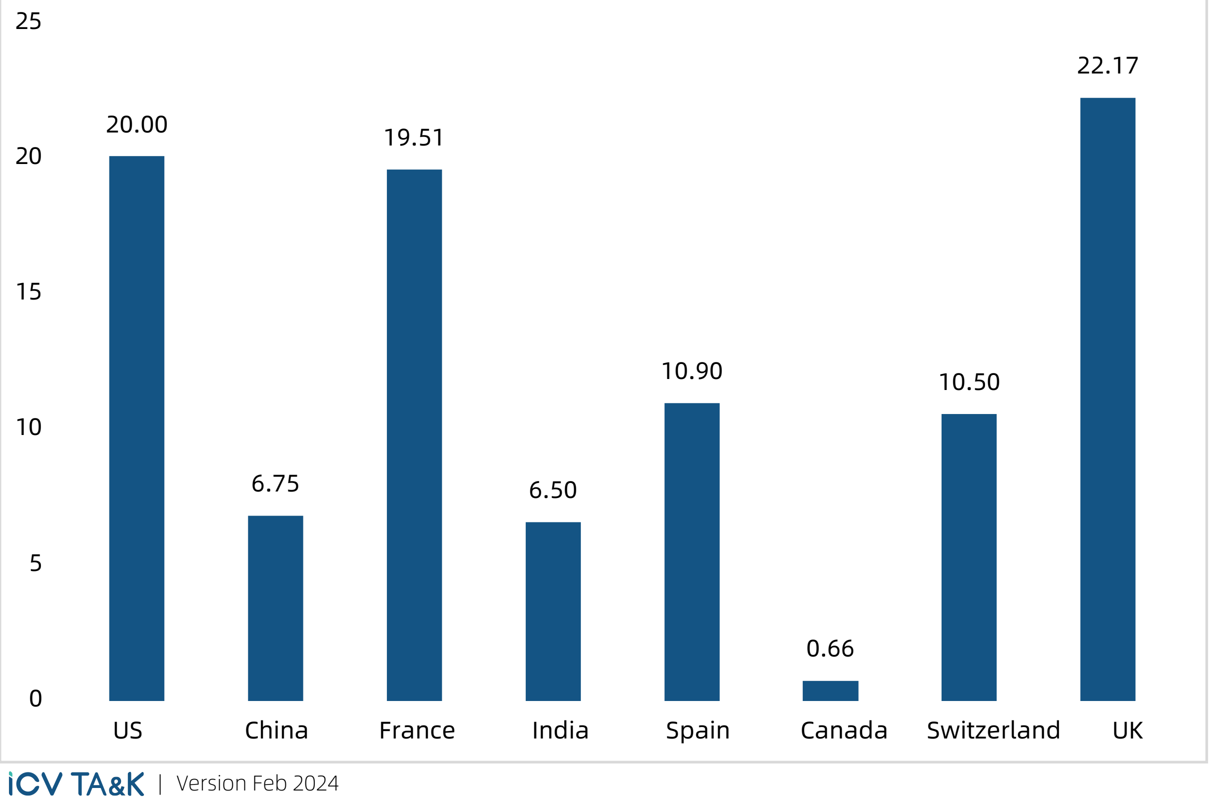
Figure: Total Global Quantum Computing Financing from 2020 to 2023 (Unit: $M)



02 Financing Geographical Distribution
The majority of funds were directed towards companies in the United Kingdom, followed by the United States and France.

In 2023, the invested companies came from 8 countries (United States, China, France, India, Spain, Canada, Switzerland, United Kingdom). Based on the disclosed financing amounts (excluding undisclosed amounts for Aliro Quantum in the United States, Crypto Quantique in the United Kingdom, Quside in Spain, Quantum Technology in China, and Terra Quantum in Switzerland), the highest amount of funds was directed towards companies in the United Kingdom (approximately $22.17 million, 3 companies), followed by companies in the United States (approximately $20 million, 1 company), France (approximately $19.51 million, 3 companies), and Spain (approximately $10.9 million, 1 company).

Figure: Financing Amount in the Global Quantum Communications and Security Field in 2023 (by country) (Unit: $M)



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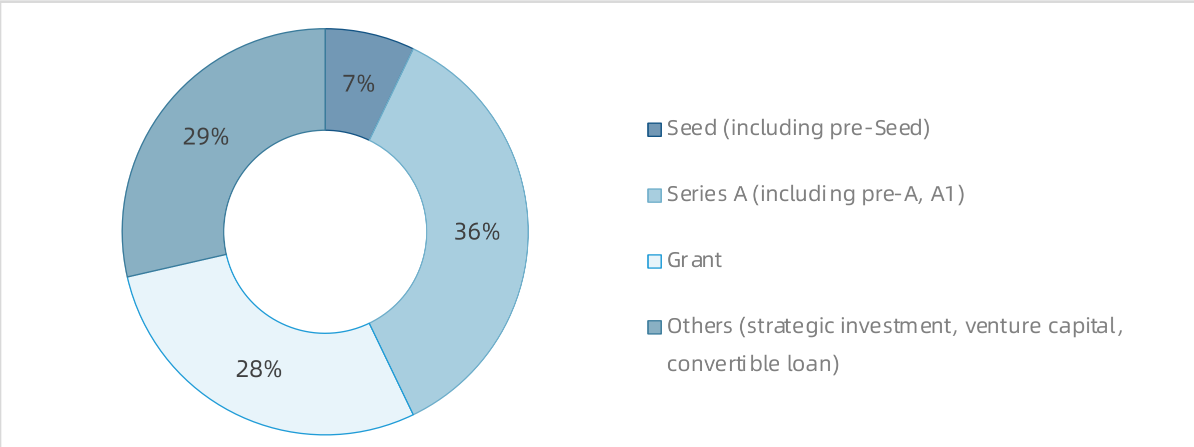
03 Financing Type

Financing type was mainly comprised of Series A rounds and other strategic investments, with no investments occurring beyond Series B rounds.

This financing analysis categorizes financing types into seed rounds (including Pre-seed), Series A rounds (including Pre-A, Pre-A1), government grants, and others (strategic investments, venture capital, convertible loans). From the perspective of financing types, Series A rounds are the most common (5 times, accounting for 41.67%), indicating that companies in the field of quantum communication are still in the early stages of development and require early-stage financing as well as government investment.

It is worth noting that in 2023, there were no quantum communication companies that completed financing rounds beyond Series B. This may be influenced by the fact that the market is still in its early stages of development, leading investors to be more cautious. Additionally, global economic and political uncertainties, technological risks, and intense competition may cause investors to adopt a wait-and-see approach, waiting for more market validation and emerging leaders to stand out. This conservative stance may result in relatively reduced investment in the quantum communication field by the capital market.

Figure: The Comprehensive Funding Situation of Global Quantum Communication and Security Companies in 2023



The funding rounds of global quantum communication and security companies				
Round	QKD (quantum repeater, quantum memory)	QRNG	PQC	Quantum Network
Seed	Welinq			
A	Q→NU		CRYPTONEXT SECURITY; 量安科技 PQCTECH	Aliro QUANTUM; nu QUANTUM
Grant	Quantum Bridge	QUSIDE; QUANTUM DICE	CRYPTO QUANTIQUE	
Others		硅臻 SILICON EXTREME	QUANTUM RESISTANT CRYPTOGRAPHY	Terra Quantum; VeriQloud

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04 Financing Field
Financing amounts across industries showed relatively minor differences.

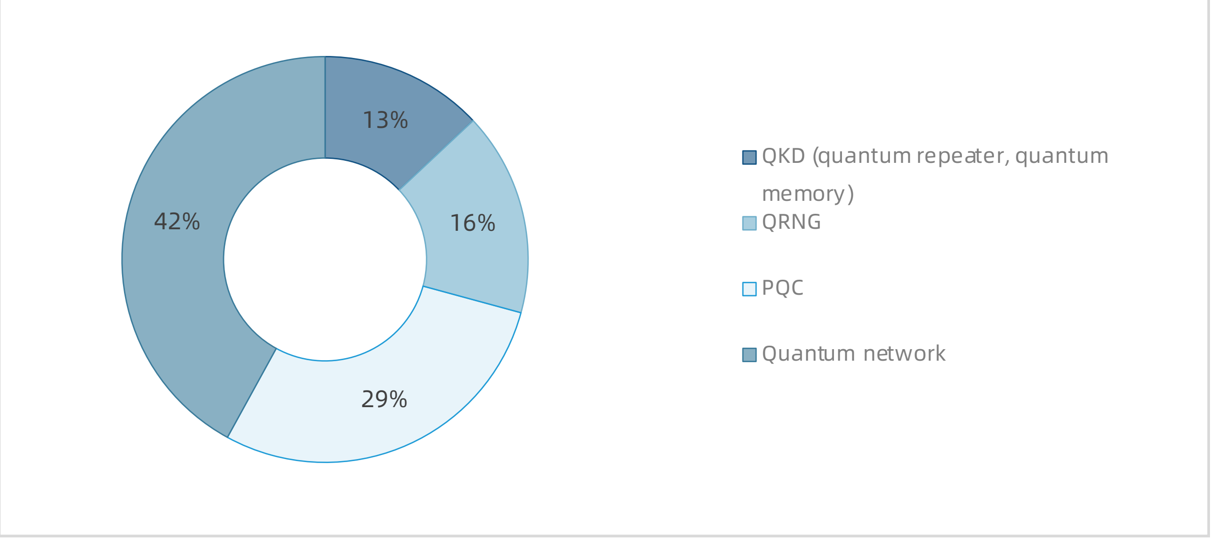
In 2023, enterprises in the field of quantum communication and security were mainly divided into three categories: PQC hardware (including QKD, QRNG, quantum relays, quantum memory), and quantum networks.

According to the compiled data, in 2023, a total of 6 enterprises obtained financing to promote the development of hardware facilities (such as QKD, QRNG, quantum relays, quantum memory) in the field of quantum communication and security. These companies include QNU Labs from India, Welinq from France, Hefei Silicon Zen from China, Quside from Spain, Quantum Bridge from Canada, and Quantum Dice from the UK, with a total financing amount of $28.3486 million.

In the PQC industry sector, 4 companies received financing, including Cryptonext Security from France, Quantum Technology from China, QRCrypto from Switzerland, and Crypto Quantique from the UK, with a total financing amount of $27.89 million.

Additionally, 3 quantum network companies received investments, namely VeriQloud from France, Aliro Quantum from the United States, Nu Quantum from the UK, and Terra Quantum from Switzerland, with a total financing amount of $40.751 million.

Figure: Distribution of Quantum Communications and Security Financing in 2023

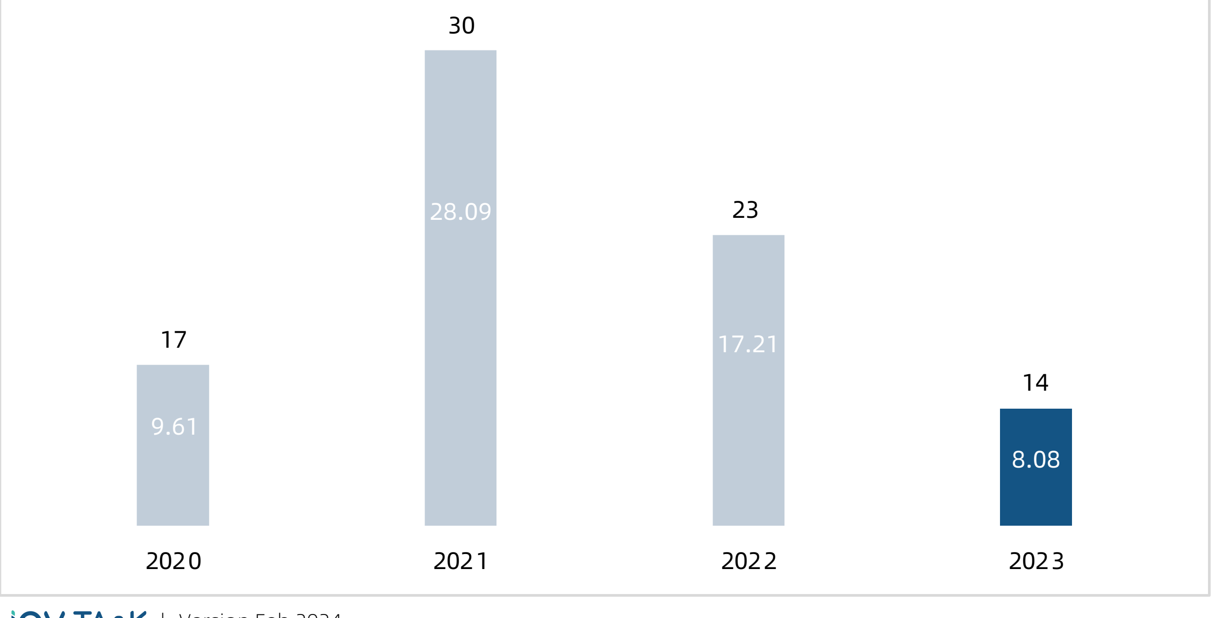


05 Financing Round
The number of financing rounds has been decreasing annually since 2021.

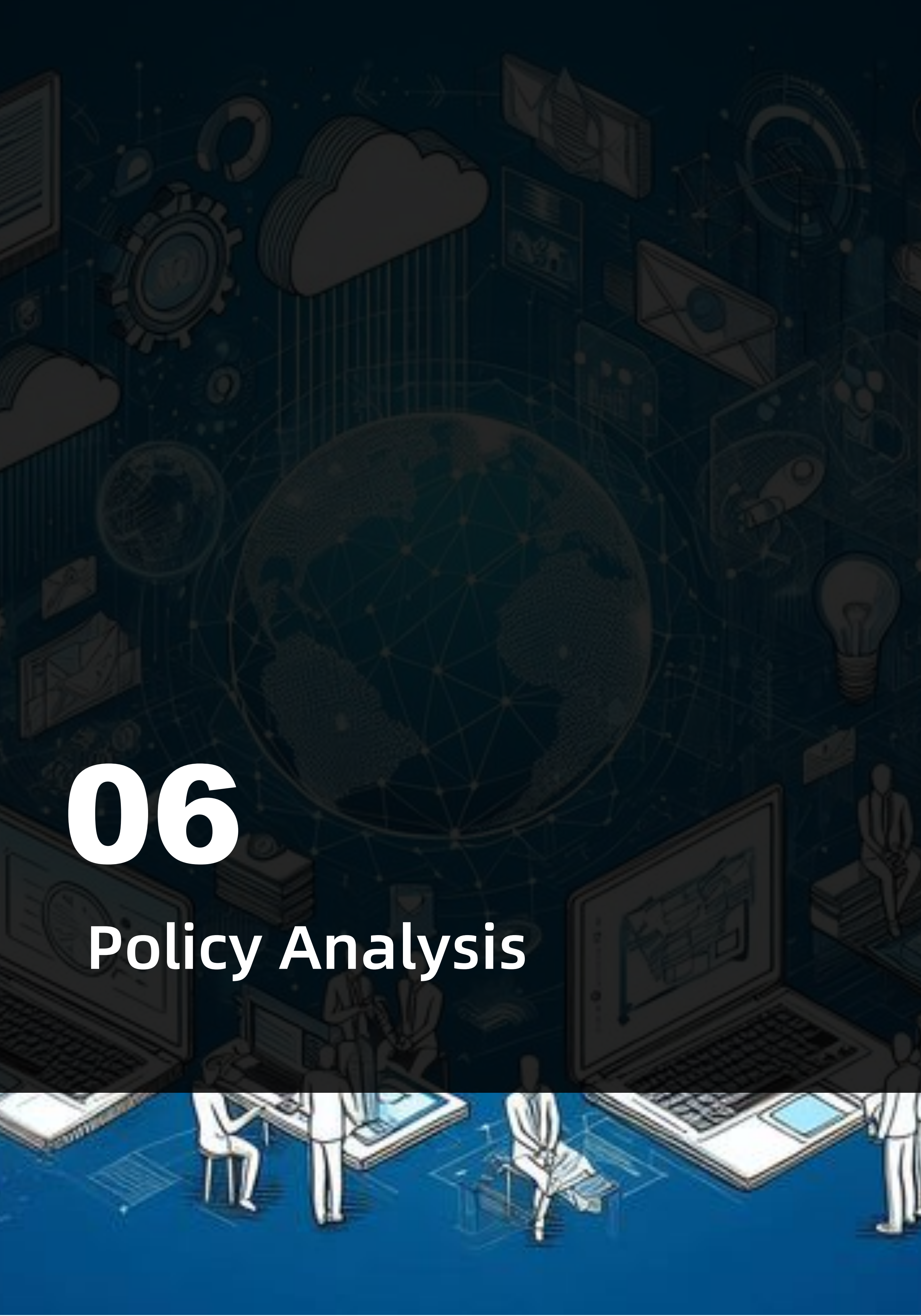
In 2023, a total of 14 financing events occurred in the field of quantum communication and security, which is lower than the number of financing events in 2022. Additionally, the average financing amount in 2023 was $8.08 million, significantly lower than that in 2022.

Since 2021, both the number of financing rounds and the average financing amount in the field of quantum communication and security have been decreasing annually. From a technological perspective, quantum communication and security belong to an emerging technology field, and the current level of technological maturity is insufficient to meet the demands of large-scale commercial applications. Although projects such as Hefei Quantum Metropolitan Area Network in China and the EuroQCI project in the European Union are gradually being constructed and operated, there is still room for improvement in terms of technological maturity and practical applications. Therefore, investors need to bear high risks in various aspects, leading to a decrease in investment enthusiasm. Furthermore, the development of quantum communication and security is becoming increasingly competitive, and investors' risk awareness is also increasing, directly affecting their investment willingness and capital input.

Figure: Number of Quantum Communication Investment and Financing Events and Average Event Amount Worldwide (2020-2023, Unit: $M)



Despite the recent decline in financing in the field of quantum communication and security, governments worldwide are actively laying out plans for the development of quantum communication and security and have implemented a series of policy measures to promote research and application in quantum communication. For example, in January 2023, Canada released the "National Quantum Strategy," which explicitly stated the intention to ensure Canadians' privacy and network security in the quantum world through quantum communication networks and post-quantum cryptography programs. Additionally, China, the European Union, and others have issued relevant policies to support the development of quantum communication and security. Therefore, with the increasing support from policies and the continuous maturation of technology, investment in the field of quantum communication and security is expected to gradually rebound.



06

Policy Analysis

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Policy Analysis

This chapter focuses on the policy formulation and implementation by governments in the field of quantum communication and security. It encompasses the attention given to the security aspects of quantum communication, the development of related technologies, and the positioning of these endeavors within national strategies. The section provides a summary of policy measures adopted by various countries to advance quantum communication and security. It is worth noting that broad policy categories, such as quantum information technology policy, are not analyzed and summarized in this chapter. For details on policies supporting quantum development in 2023, please refer to the appendix.

United States of America

Migration to Post-Quantum Cryptography

The National Cybersecurity Center of Excellence (NCCoE) has released the "Quantum Ready: Transitioning to Post-Quantum Cryptography" guide, outlining recommendations for developing a quantum-ready roadmap, preparing an encryption inventory, understanding and assessing supply chain considerations, and providing guidance on how organizations should engage with their technology suppliers regarding post-quantum cryptography, along with delineating the responsibilities of technology suppliers. Furthermore, NCCoE has published a list of the latest 28 technology suppliers participating in the project, including industry leaders such as IBM, Microsoft, Amazon, and others.

This policy guide encourages organizations to first establish a project management team to plan and determine the scope of their transition to Post-Quantum Cryptography (PQC), thereby creating a quantum-ready roadmap. Subsequently, organizations are advised to prepare an inventory of cryptographic assets. Those systems and assets vulnerable to quantum attacks can initiate the quantum risk assessment process to prioritize migration. Collaborating with PQC vendors on the PQC migration roadmap can follow. Lastly, organizations should prepare their suppliers within the supply chain for PQC. It is crucial for organizations to understand how their suppliers are addressing quantum readiness and PQC migration. Throughout this process, priority should be given to high-impact systems, control systems, and systems with long-term secrecy requirements.

Draft: Migration to Post-Quantum Cryptography Quantum Readiness: Cryptographic Discovery

The draft document titled "Quantum Readiness: Cryptographic Discovery for the Migration to Post-Quantum Cryptography," released by NIST, outlines a functional testing plan that mandates the use of cryptographic tools to identify insecure configurations in digital networks. It further describes use case scenarios to provide deployment scenarios for a successful transition to post-quantum systems. This draft underscores that the initial step in supporting PQC migration is to pinpoint the locations and purposes of public key encryption used within the enterprise. Subsequently, organizations should identify and prepare an inventory of migratable assets, such as hardware and software. This component is a core functionality within the cybersecurity framework and represents a fundamental prerequisite for any organization effectively managing cybersecurity risks.

Draft: Migration to Post-Quantum Cryptography Quantum Readiness: Testing Draft Standards

NIST's draft document, "Quantum Readiness: Testing Standards for the Migration to Post-Quantum Cryptography," underscores the need to coordinate quantum-resistant algorithms with existing network infrastructure. It provides solutions for compatibility issues in a controlled non-production environment and addresses the coordination and integration challenges between PQC algorithms and current infrastructure, offering compatibility solutions. The draft outlines two specific aspects focused on addressing challenges in the PQC migration process: identifying systems vulnerable to quantum attacks and testing the interoperability and performance of PQC algorithms.

Republic of Korea

Preparing for the Quantum Transformation Era（양자 대전환 시대 대비）

The PQC cryptography master plan "Preparing for the Era of Quantum Transformation" released by Republic of Korea's National Intelligence Service and the Ministry of Science, Technology, Information and Communications states that it will transform its national cryptography system into PQC by 2035. This plan contains three overall goals: first, formulate detailed action plans in six aspects, including technology acquisition, system improvement, and procedure formulation, to establish policy directions for the transition to a national medium- and long-term cryptographic system in 2024; second, establish a "pan National Cryptosystem Transition Promotion Group" to lay the foundation for the transition to the PQC system by 2030; third, establish a technical and policy support system for the transition to PQC by 2035, and implement a secure cryptography system.

European Union

The European Quantum Communication Infrastructure (EuroQCI) Initiative

The EuroQCI project aims to integrate quantum-based systems into existing communication infrastructure to safeguard sensitive data and critical facilities, providing an additional layer of security based on quantum physics. It will strengthen the protection of European government agencies, data centers, hospitals, energy networks, among others, becoming a key pillar of the European Union's network security strategy for the coming decades. The first implementation phase of EuroQCI commenced in January 2023.

The project will leverage innovative quantum communication technologies, including those developed by researchers funded by the European Union's Quantum Technology Flagship program, particularly building upon the activities of the Horizon 2020 OPENQKD project. The participation of European industry partners and small to medium-sized enterprises is crucial to ensuring that key components of EuroQCI are based on European technology. This involvement will ultimately enhance Europe's scientific, technological, and industrial capabilities in network security and quantum technology. Consequently, the initiative will contribute to European digital sovereignty and industrial competitiveness, aiding in the realization of the European Digital Decade plan, with the goal of positioning Europe as a leader in quantum capabilities by 2030.

07

Industry Analysis and Forecast

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Industry Analysis and Forecast

量子信息与安全领域的产品及技术服务主要归属于网络安全领域，是庞大的网络安全产业中的一个较为核心和根本的子产业，可向下扩展至涉及多个行业的安全产品。

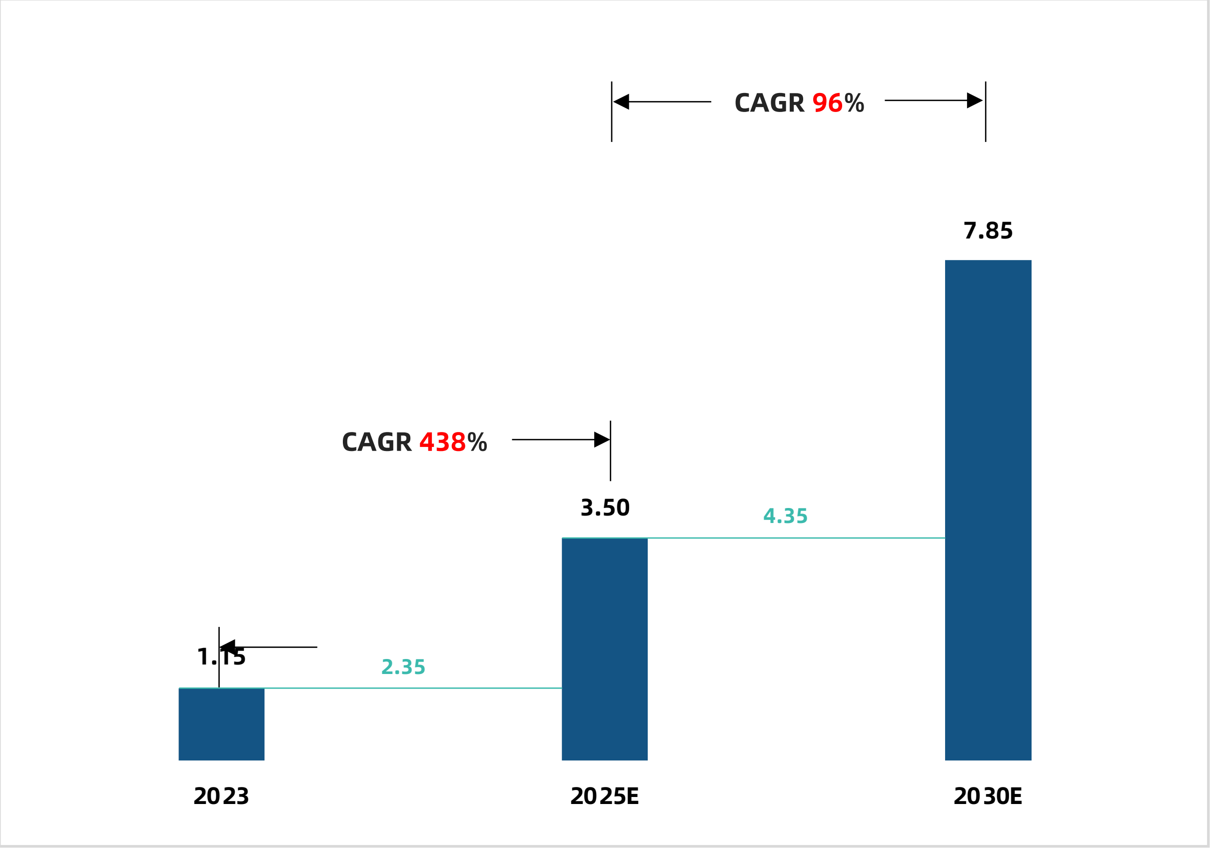
量子信息与安全产业从目前已经发展的形态来看，主要是由量子物理加密产品与技术（例如QKD）、PQC、QRNG等带来的产业价值。

QKD Industry Scale Forecast

QKD产品技术发展已较为成熟，目前主要集中在产品的升级迭代，以提升性能、优化价格应用竞争力、缩小整机尺寸、用户友好性和产品的可扩展性等方面。QKD产品是网络安全领域中一种补充和增强的手段。QKD产品的发展方向将更多地关注于不同领域的深度融合，为安全通信提供更为全面和创新的解决方案。随着技术的不断成熟和市场对高度安全性的需求增加，QKD作为一种补充手段将在网络安全领域发挥越来越重要的作用。

2023年全球QKD市场规模较2022年有所增长，为11.54亿美元。随着全球经济的逐步恢复，QKD的应用场景逐渐清晰与增多等，未来几年将是QKD行业快速增长阶段，到2025年，预计市场规模将达到35.04亿美元。

Figure: Global QKD Industry Scale (2019-2025E, Unit: $B)



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国防军事领域是QKD当前最主要的应用市场，未来，随着QKD技术的提升和市场对QKD技术的认可，其他行业应用规模的增加。

Figure: Global QKD Downstream Application Forecast (2023-2025E)

Segment Share	2023	2024E	2025E
Defense & Military	25.65%	25.85%	26.11%
Telecommunications	10.05%	10.42%	10.53%
Government Affairs	10.05%	10.22%	11.70%
Power Grid	22.53%	21.36%	16.41%
Finance	15.94%	16.41%	17.55%
Rail	12.31%	12.64%	15.41%
Others	3.47%	3.10%	2.28%

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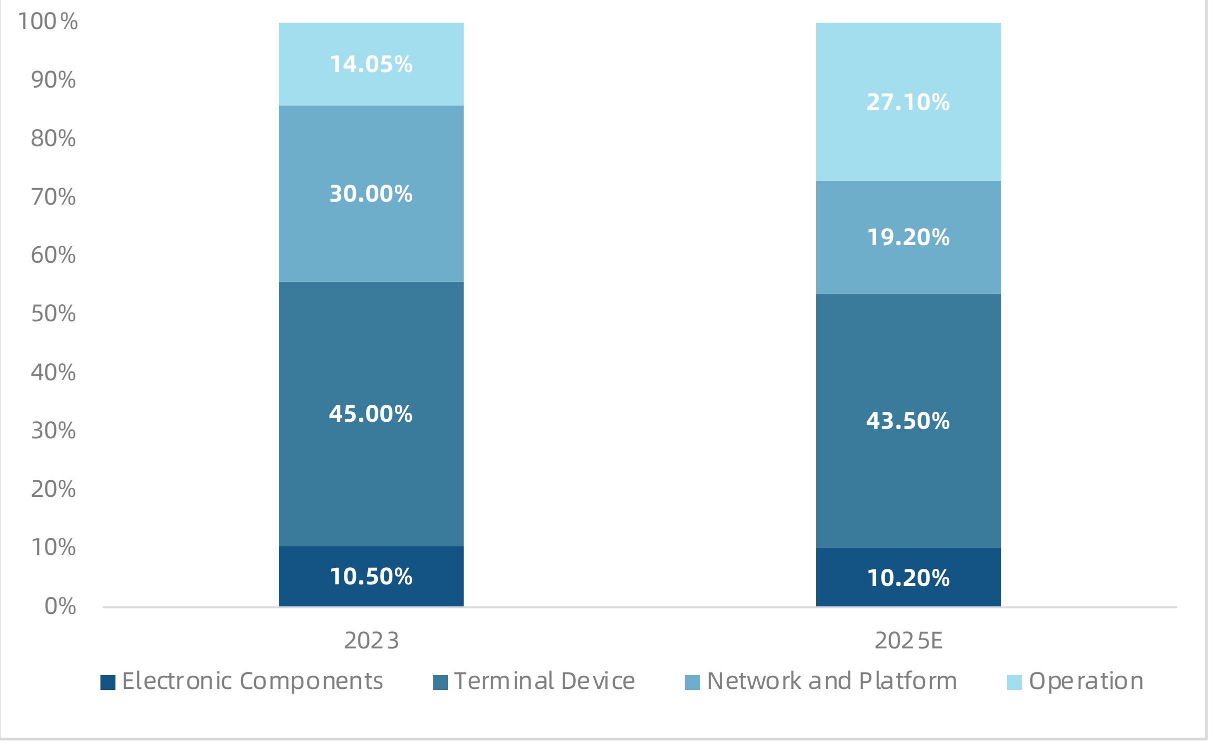
从产业链主要环节的结构占比来看，在技术不断进步的推动下，大规模应用带来的成本下降以及元器件供应稳定等因素影响，预计到2025年元器件在整个产业结构中的占比将略微下降。而未来几年，终端设备市场将是产业中最主要的增长领域。

预计到2025年，网络和平台搭建的规模占比将降低，这是由于主要国家已进行了大规模的网络基础设施建设，使得网络和平台搭建的需求相对减弱。

Figure: Global QKD Industrial Structure (2023-2025E)



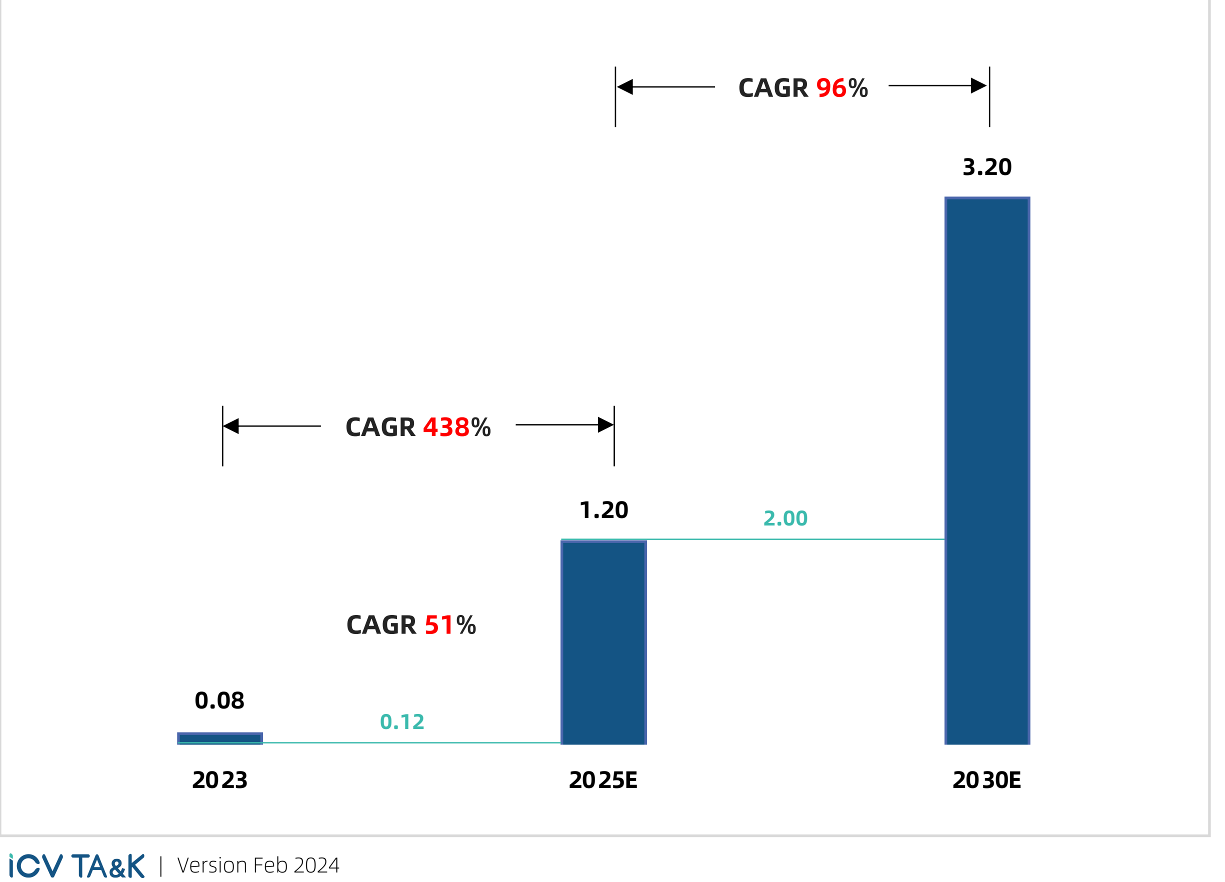
QRNG Industry Scale Forecast

由于对安全通信和数据保护的需求不断增加，QRNG应用场景也在不断增加。目前，QRNG在各个领域都有应用，包括汽车、手机、物联网 以 及 其他市场。在汽车行业，QRNG芯片用于安全通信和加密，增强车辆网络安全。手机 也 受益于QRNG芯片，可确保安全交易并保护用户敏感数据。在物联网和边缘设备领域，QRNG为通过互连设备传输的关键信息提供安全保障。

未来，QRNG将会在金融服务、医疗保健和国防等多个行业中不断整合，在这些领域中对安全通信、数据存储和数字交易的需求将为QRNG产业发展创造丰富的机会，推动QRNG市场规模增长。

2023年，全球QRNG产业规模约为8,000万美元。随着QRNG芯片技术趋于成熟，以及各方对其认知度的提高和下游应用普及，预计到2025年，全球QRNG产业规模将扩大至2.03亿美元；预计到2030年，QRNG产业规模将达到225亿美元。

Figure: Global QRNG Industry Scale (2023-2030E, Unit: $B)



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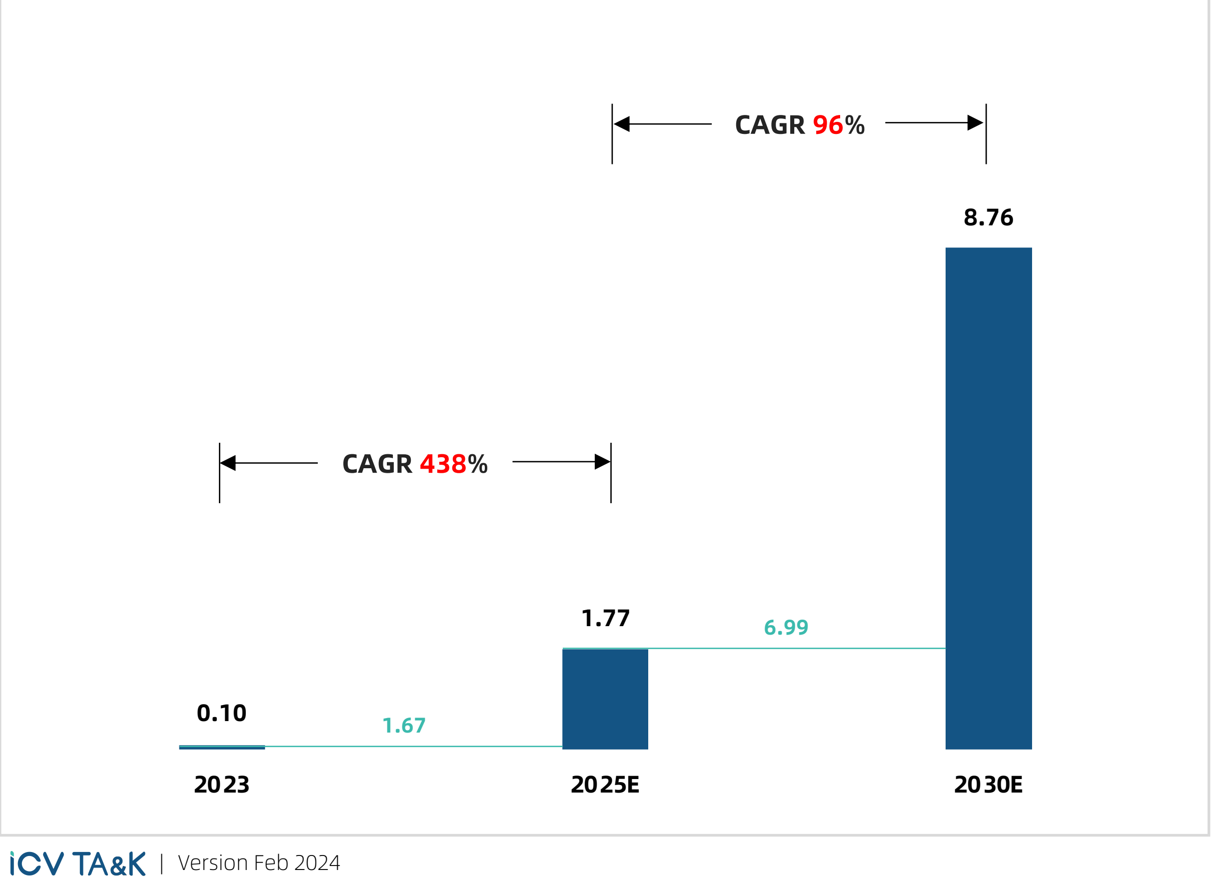
PQC Industry Scale Forecast

PQC是对当前密码体系进行升级和强化的一项措施。在量子计算技术尚未成熟时，对现有安全产业的影响有限。随着量子计算能力以及数据安全需求的不断提升，未来必然会出现新的安全软件或安全芯片。随着PQC技术的成熟和市场认知的提高，PQC将逐渐渗透到各个领域。

PQC产品的两大主要形式，即软件和硬件，为应对不同领域和应用场景的安全需求提供了多样化的选择。软件类产品，包括先进的PQC算法，将能够在各种软件系统中实现更高层次的安全性，尤其是在浏览器等网络通信环境中发挥关键作用。硬件类产品，如模块化设备和嵌入芯片，将为下游行业的硬件系统提供更加可靠和强大的安全解决方案。

PQC市场增长与PQC标准化进程及量子计算机的实用化有较大关联。2023年PQC产业规模处在初期成长阶段，约为1亿美元。根据NIST的PQC标准化工作预计完成的时间点（2024年），我们预计2024年后，行业将迎来小幅加速发展。预计到2025年，全球PQC产业规模将达到17.7亿美金；预计到2030年，全球PQC产业规模将达到509.1亿美元。

Figure: Global PQC Industry Scale (2023-2030E, Unit: $B)



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08

Industry Outlook

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Industry Outlook

01
QKD deployment continues to expand its scope

Over 30 countries worldwide are deploying or have already implemented QKD infrastructure construction, including China, European Union member states, Canada, the United Kingdom, Republic of Korea, Singapore, and others. Driven by these countries, the construction work and application scenarios of QKD have expanded to different extents on the ground and in space.
In terms of ground and space network layouts, as of January 2023, the EuroQCI project of the European Union has seen most countries entering the construction phase, with continuous support in policies and funding actively pushing the construction of quantum communication infrastructure. All EU member states (a total of 26 countries) have also initiated transnational cooperation in the construction of QKD infrastructure. Through cooperation, they integrate resources from different countries to accelerate the layout and construction of QKD networks, promoting the establishment of standards and the improvement of interoperability. Moreover, China is also continuously expanding the coverage of its backbone network in QKD infrastructure construction, having completed the construction of a quantum secure communication backbone network in the Yangtze River Delta region in 2023.

In terms of application field layout, the deployment in different industries such as finance, government affairs, defense, communications, and power grids has driven the industry application of QKD, encouraging more business trials of QKD infrastructure networks in a wider range. For example, HSBC bank tested the application of QKD technology to the security of foreign exchange trading systems and successfully completed a transaction of 30 million euros converted to US dollars. In terms of QKD satellite construction, Singapore's SpeQtral company will collaborate with NanoAvionics and Mbryonics to construct a QKD satellite, exploring future application scenarios.

02
Research on fundamental technologies such as QKD remains a focus for future efforts

The core of Quantum Key Distribution (QKD) lies in ensuring the security of information transmission. Significant achievements have been made in the application research transitioning from "0 to 1," while foundational research moving from "1 to 0" can provide theoretical support for designing more secure and efficient QKD systems. Through a reciprocal enhancement between the stages of "0 to 1" and "1 to 1," advancing fundamental research in protocols, control technologies, and chip-scale technologies can uncover new quantum communication security schemes, thereby enhancing the attack resilience of QKD systems.

On one hand, foundational research is crucial for addressing practical challenges faced by QKD technology, such as photon loss, noise interference, transmission rate, and economic viability of applications. For instance, control technology involves precise manipulation of quantum bits, including the operation of photons and other quantum information carriers, to ensure stability and accuracy during transmission and processing. In QKD systems, advancements in control technology can reduce error rates and enhance communication security. By delving into these basic scientific issues, effective methods and technical support can be provided for solving practical and economic engineering challenges, propelling QKD technology towards real-world application. Notably, although the European EuroQCI project has commenced, it will progressively refine foundational QKD technology research, complete technology testing, and evaluation to enhance the performance of quantum communication network infrastructure.

On the other hand, quantum secure communication protocols, as key mechanisms to safeguard quantum communication security, require continuous optimization and improvement. Protocol research is also crucial. By conducting in-depth studies of protocols to accommodate different communication environments and needs, more flexible and efficient secure system designs can be achieved, thereby enhancing the applicability and robustness of secure systems in practical applications.

03
The development of PQC is about to enter a growth period

With the advancement of standardization efforts in the Post-Quantum Cryptography (PQC) field by the NIST, along with the release of numerous PQC-related documents in the United States, Canada, and Republic of Korea, PQC technology is poised to move from its nascent stage into a period of growth. The progression of standardization efforts and the issuance of various policy documents will eliminate policy barriers for the development of PQC technology, facilitating broader awareness and fostering the development of this emerging technology.

Firstly, the PQC standardization work led by NIST, which has spanned eight years, is about to complete the first phase of the PQC standard draft. This signifies that PQC technology is entering a stage of commercialization and exploration of potential applications. Although the PQC algorithms nominated by NIST still have security vulnerabilities, the demand for secure network information and concerns about the decrypting capabilities of quantum computing are driving forces for the continuous upgrading of PQC technology. As PQC algorithms evolve and improve, the technology is expected to gradually optimize, potentially addressing various practical application scenarios across different fields and scales.

Secondly, in the future, more companies will experiment with or emerge in the PQC technology field, competing to develop and provide PQC solutions to address the challenge of "store now, decrypt later" posed by quantum computing. The emergence of PQC companies will further promote the business development of the PQC field, and the industrial chain of PQC is expected to become more comprehensive.

Lastly, the scale of investment and financing in the PQC field is expected to increase. Against the backdrop of a global economic downturn, investment in previously focused areas such as Quantum Key Distribution (QKD) and Quantum Random Number Generation (QRNG) has declined compared to the past two years. However, investment in the PQC field shows a year-on-year upward trend. As continuous exploration in PQC technology research and application progresses, and as it gradually embeds in practical applications showcasing its commercial potential, more capital is likely to flow into this area, heralding a larger scale of investment and financing to propel the development of the PQC field.

04
PQC migration plans and commercialization are gradually beginning

The advancement of Post-Quantum Cryptography (PQC) commercialization has led numerous enterprises and organizations to seek migration from existing encryption algorithms to PQC frameworks. This shift not only drives commercial development but also places increased emphasis on the practical commercial applications and cost-effectiveness of PQC technology. Notably, in June 2023, the United States Army contracted with QuSecure, and the United States Defense Information Systems Agency contracted with SandboxAQ, requiring these technology companies to provide PQC encryption technologies and solutions. The involvement of government units in PQC applications serves as a leading example, propelling the commercial application and migration plans of PQC research.

In terms of PQC migration, the United States National Institute of Standards and Technology (NIST) released "Getting Ready for Post-Quantum Cryptography: Cryptographic Discoveries" and "Getting Ready for Post-Quantum Cryptography: Test Draft Standards" in December 2023. These publications outline potential issues that may arise during the migration to PQC and possible solutions. The former describes a PQC functionality testing plan and use case scenarios, while the latter highlights the coordination issues between PQC and existing networks, providing solutions. Earlier, the United States National Cybersecurity Center of Excellence also published "Migrating to Post-Quantum Cryptography," explaining the background, objectives, challenges, benefits, and workflow of PQC migration. The release of these documents marks a more systematic and standardized phase of PQC migration, also showcasing the certainty of the impending PQC era.

Commercially, several companies have released and iterated PQC software, hardware, and solutions, such as WISeKey, QuSecure, and Quantum Xchange, supporting this new method to ensure communication and data security. As the commercialization and migration plans of PQC progress, an increasing number of enterprises will be able to utilize PQC technology to establish secure defenses, protecting corporate and personal vital information from the threats posed by the breaking of current algorithms.

05
Global quantum policies favoring the industry will continue to ensure its positive development.

At the level of project research support, many countries are investing in research funding in the field of quantum communication and security. For example, the Canadian government, along with the government of Quebec, has invested over 10 million Canadian dollars to provide a quantum communication experimental platform in the DistriQ Quantum Innovation Zone in Montreal, Quebec City, and Sherbrooke. The German Federal Ministry of Education and Research funds projects like Chip-Based Quantum Random Number Device (CBQD), focusing on researching quantum secure high-speed communication.

At a higher level of national policy, in 2023, some countries released their first national quantum strategies, while others, like the UK, released their second decade-long national plans. These documents provide strong support for the continued development of quantum communication. For example, countries such as the UK, Canada, and Australia released their national quantum strategies in 2023, including policies to support the development of quantum communication. Japan introduced the Quantum Future Industry Innovation Strategy, setting three goals for the future to be achieved. India's national quantum mission aims to build satellite-based secure quantum communication within a 2000 km range in India, long-distance secure quantum communication with other countries, urban quantum key distribution over distances exceeding 2000 km, and the establishment of a multi-node quantum network with quantum memories within the country within the next 8 years. Republic of Korea introduced the Quantum Technology and Quantum Industry Promotion Act, establishing comprehensive plans for the development of industries in various fields including quantum communication and the construction of a technological system. Meanwhile, the United States has formulated guidelines and action plans for PQC migration.

06
Although there has been an increase in international cooperation, obstacles and barriers still exist.

Currently, we can observe some cooperation among countries in the field of quantum communication and security. For instance, in October, the United States and Singapore initiated a Critical and Emerging Technologies (CET) dialogue, mentioning their intention to enhance information sharing on PQC migration. In 2023, the United States and the Netherlands also issued a Joint Statement on Quantum Information Science and Technology (QIST), aiming to advance bilateral development in quantum networks and other specific areas. Canada and the United Kingdom signed a Memorandum of Cooperation (MOC) to strengthen collaboration in quantum information technology, supporting mutual market development, enhancing the quantum product supply chain, and establishing a talent pool for quantum workforce needs.

However, due to the possibility that related technologies may involve information security and even national security, differences in technological capabilities among countries, and the competitive relationship among major participating countries, information sharing may only occur within a certain scope, and cooperation among nations always involves strategic considerations.

Additionally, commercial cooperation is subject to restrictions imposed by relevant national regulations, influenced by international relations. For example, in August, the United States issued new regulations restricting U.S. investment in advanced technology industries in certain countries, limiting investments by U.S. private equity and venture capital firms and joint ventures in artificial intelligence, quantum information technology, and semiconductor fields in some countries. In October, the European Union published a sensitive technology list containing 10 items, highlighting quantum technology, biotechnology, semiconductors, and artificial intelligence as the most critical. In December, the United States, Republic of Korea, and other allied countries are in preliminary negotiations to establish a new export control mechanism to prevent the transfer of cutting-edge technologies, including semiconductors and quantum computing, to potential adversaries.。

07
Quantum communication, quantum computing, and quantum precision measurement mutually promote each other, giving rise to new opportunities.

In the field of information technology, data and computations generated in computing, communication, sensing, and other areas often intersect, prompting some strong companies or those seeking to bridge these intersections to engage in cross-domain research and business layout at opportune moments. This trend became more apparent in 2023. For example, IBM Quantum, which previously focused primarily on quantum computing and led in the commercialization of quantum computing, released its first quantum security roadmap in 2023. Additionally, it collaborated with companies like Vodafone on quantum security. This roadmap not only expanded IBM's technical scope but also included quantum communication steps applicable to practical scenarios. Furthermore, IBM plans to launch quantum bit systems connected through quantum communication by 2025, facilitating closer integration between quantum computing and communication domains.

Moreover, there have been initial successes in leveraging quantum computing to enhance the security of quantum communication. For instance, Quantinuum company utilized quantum computing technology to reinforce key security, providing fundamental protection for data transmission.

In the future, cross-disciplinary collaborations among computing, communication, security, and precision measurement will become more common. More companies will leverage the unique properties of quantum computing and quantum precision measurement to enhance the security of quantum communication. The mutual promotion among these three domains will form a more comprehensive quantum ecosystem.

08
The future development of PQC and QKD will proceed hand in hand.

QKD and PQC are two key and practical branches of technology in the current field of quantum communication and security. In earlier years, the development progress and societal awareness of QKD were significantly higher than that of PQC. However, in recent years, the attention towards PQC has rapidly increased. Currently, in terms of investment, related policies, research popularity, and commercial expectations, the development momentum of both QKD and PQC is generally equivalent.

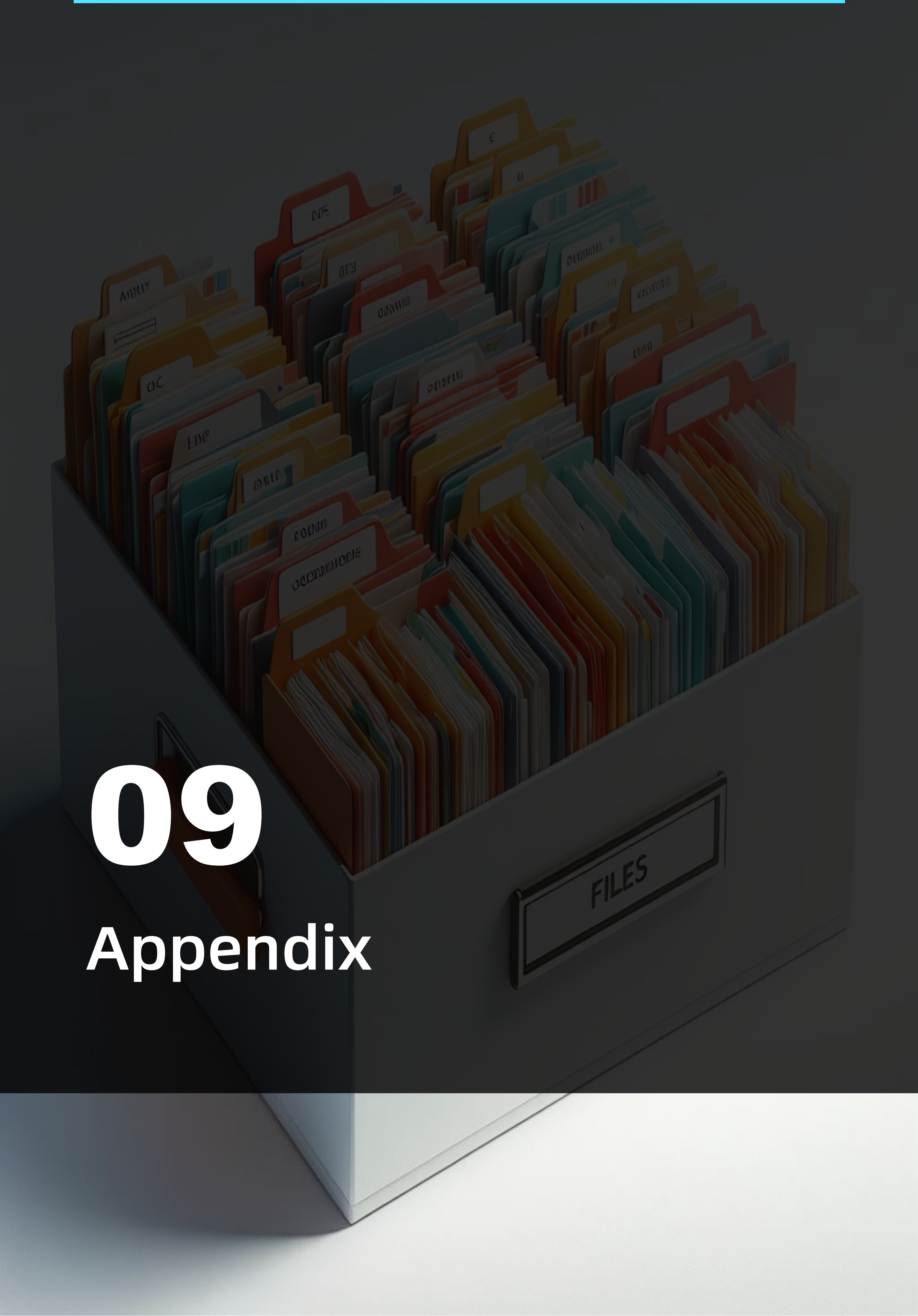
In terms of investment amount, both QKD and PQC attracted substantial funding in 2023. The more established QKD technology, due to its solid foundation, has always been favored and received a certain level of financial support. As the understanding of PQC deepens, PQC has gradually become a focus of investors' attention. The financing data for 2023 shows that there is some competition between QKD and PQC in terms of funding amount, with PQC receiving approximately $27 million and QKD around $12.6 million.

From a policy perspective, several countries have issued policies supporting the development of quantum technology in 2023. Although different countries have different focuses on QKD and PQC, most countries hold a supportive attitude towards the development of both types of technology. Both QKD and PQC have benefited from policy support, which has facilitated their technological research and commercialization.

Finally, different countries have different emphasis on the development of QKD and PQC. For example, the United States is more focused on the development and migration of PQC technology, while China and the European Union allocate more resources to QKD technology and implement infrastructure construction. It is currently unknown which of these two technologies will occupy a dominant position in the future, or whether they will mutually support and integrate with each other. In the years when the technological and market landscape is being shaped, QKD and PQC will exist in a competitive relationship on a global scale, each leveraging its strengths to promote continuous technological advancement and prepare for the comprehensive arrival of the quantum era.

09

Appendix



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Appendix

01 Supplier Evaluation System (CTF Model)

The CTF (Capability, Traction, Future) model is an evaluation and analysis framework for future industry participants. ICV TA&K's CTF model serves to help the public understand the development status of cutting-edge technology fields and corresponding companies. Cutting-edge technologies exhibit characteristics such as non-convergent technological paths, high uncertainty in technology development, and early-stage commercialization efforts. With continuous technological advancements, it becomes necessary to have a rational model for evaluating companies and forming a "consensus" on specific periods of cutting-edge technology suppliers.

The CTF model consists of four sectors presented in depth, with different-sized fan-shaped regions, and is constructed using three-dimensional coordinates. The horizontal axis represents the Maturity of Technology (the technological aspects, including the supplier's technology, research and development, and team), the vertical axis represents the Commercialization of Technology (the business aspects, including the supplier's revenue, customers, and use cases), and the implicit variable represents the underlying factors (the long-term operational elements accumulated by the supplier that can drive enterprise development). Based on the supplier's comprehensive performance in different dimensions, the CTF model classifies them into the following four sectors: Pilot, Overtaker, Explorer, and Chance-seeker.

Due to the rapid growth and high uncertainty inherent in emerging technologies, CTF diagrams for various subfields need to be updated periodically.

- Fan1—Pilot: The characteristic of companies in this sector is that they have relatively large enterprise scales and have accumulated considerable experience during the previous technology development cycles. This solid foundation enables them to enter new frontiers of technology confidently. These companies possess the capability and resources to become leaders in the new wave of cutting-edge technologies, potentially exerting a profound influence on the future direction of the industry.
- Fan2—Overtaker: Companies in this sector, after a period of development, have begun to establish a certain scale. One of their major advantages is their robust capability in new technology research and development. Leveraging their accumulated expertise in specific technological domains, these companies are poised to "overtake" and emerge as industry leaders in the future.

- Fan3—Explorer: This sector comprises smaller-sized companies, yet they have ventured into the path of emerging technologies relatively early. The development of specific technologies is still in its early stages, and compared to Pilots and Overtakers, they often have a gap in overall technological prowess.
- Fan4—Chance-seeker: The companies in this sector possess keen business acumen and are emerging players in the industry. They are not large in scale but have founding team members with some resources, enabling the company to seize opportunities for growth in new domains. These companies currently have few product engineering prototypes and limited market exposure opportunities.

The CTF model can assist clients in the forefront of technology in evaluating procurement and investment in a particular technology vendor. It's crucial to note that suppliers in the Pilot quadrant aren't always the best choice. Depending on the specific needs of the enterprise, companies in the Overtaker or Explorer quadrants might be the better option.

02 Government Funding Programs in 2023

In 2023, a total of 9 countries/organizations globally (excluding China) unveiled government-led funding initiatives/projects in the field of quantum information technology. Among these, the European Union initiated 12 programs/projects, amounting to approximately EUR 266 million (approximately USD 290 million). The United States launched 9 programs/projects, totaling around USD 46.7 million. The United Kingdom introduced 4 programs/projects, with a budget of approximately GBP 23 million (approximately USD 29 million).

Figure: Government-led quantum funding programs in 2023

No.	Time	Country/ Organization	Institute	Title	Investment Amount
1	Jan 2023	USA	Department of Energy	Quantum Horizons: Qis Research And Innovation For Nuclear Science	9.1 million USD
2	Feb 2023	USA	National Science Foundation, Department of Energy	Expanding Capacity in Quantum Information Science and Engineering (ExpandQISE)	5 million USD
3	Jan 2023	Netherlands	Quantum Delta Netherlands	Quantum Delta NL SME programme	5 million EUR
4	Mar 2023	Netherlands	Quantum Delta Netherlands	Accelerate Early-Stage Quantum Technology Startups In Nl	15 million EUR
5	Jan 2023	EU	Quantum flagship	Quantum Communication Technologies for space systems	5 million EUR
6	Jan 2023	EU	Quantum flagship	Quantum Space Gravimetry Phase-A Study	3 million EUR
7	Jan 2023	EU	Quantum flagship	Quantum Photonic Integrated Circuit technologies	12 million EUR
8	Jan 2023	EU	Quantum flagship	Investing in alternative quantum computation and simulation platform technologies	20 million EUR
9	Jan 2023	EU	Quantum flagship	Next generation quantum sensing and metrology technologies	10 million EUR
10	Jan 2023	EU	Quantum flagship	Framework Partnership Agreement for developing large-scale quantum Computing platform technologies	/
11	Jan 2023	EU	Quantum flagship	Hop on Facility	40 million EUR

No.	Time	Country/ Organization	Institute	Title	Investment Amount
12	Jan 2023	EU	Quantum flagship	Quantum Space Gravimetry Phase-B study & Technology Maturation	14.2 million EUR
13	Jan 2023	EU	Quantum flagship	Quantum sensing and metrology for market uptake	15 million EUR
14	Jan 2023	EU	Quantum flagship	Stimulating transnational research and development of next generation quantum technologies, including basic theories and components (Cascading grant with FSTP)	15 million EUR
15	Jan 2023	EU	European Innovation Council	EIC Accelerator	1.13 billion EUR
16	Apr 2023	EU	European Commission	Experimental production capabilities for quantum technologies in Europe (Qu-Pilot)	19 million EUR
17	May 2023	USA	National Science Foundation	NSF Engines Development Award	1 million USD
18	May 2023	USA	National Science Foundation	NSF Engines Development Award	1 million USD
19	May 2023	UK	Department for Science, Innovation and Technology, Innovate UK	Small Business Research Initiative (SBRI)	15 million GBP
20	Jun 2023	UK	Department for Science	/	45 million GBP
21	Jun 2023	UK	National Quantum Computing Centre	/	30 million GBP
22	Jun 2023	Canada	Alberta Government	Quantum Horizons Alberta (QHA)	25 million USD
23	Jun 2023	Denmark	Danish Government	Læs del 1 af Strategi for Kvanteteknologi: Forskning og innovation i verdensklasse	1 billion CZK
24	Jul 2023	Netherlands	Quantum Delta Netherlands	Trilateral Agreement	60.2 million EUR
25	Jul 2023	USA	Department of Energy	Quantum Testbed Pathfinder	11.7 million USD
26	Aug 2023	USA	Department of Energy	不涉及	24 million USD
27	Aug 2023	USA	National Science Foundation	不涉及	29 million USD

No.	Time	Country/ Organization	Institute	Title	Investment Amount
28	Aug 2023	USA	United States Senate	Quantum Computing Programs	44 million USD
29	Aug 2023	UK	Innovate UK	Small Business Research Initiative (SBRI)	30 million GBP
30	Sep 2023	USA	National Science Foundation	/	76 million USD
31	Sep 2023	New Zealand	Ministry of Business, Innovation and Employment	The Quantum Technologies Research Programme	1200 million NZD (5 years)
32	Oct 2023	Germany	Federal Ministry of Education and Research	Chip Based Quantum Random Number Devices	/
33	Oct 2023	Canada	Canada Government, Quebec Government	/	7.6 million CAD
34	Dec 2023	Australia	Albanese Government	Australian Centre for Quantum Computation and Communication Technology	185 million AUD

03 International Cooperation Events in 2023

Figure: Declaration of QIST Cooperation Signed by the US and Other Countries in 2023

Time	Collaborating Parties		Event
Jan 2023	USA	India	Sign the Critical and Emerging Technology (iCET) Initiative (U.S.-India Initiative on Critical and Emerging Technologies)
Feb 2023	USA Europe Canada Japan		Sign Memorandum Of Understanding (MoU)
Feb 2023	USA	Neitherlands	Sign Joint Statement on Cooperation in Quantum Information Science and Technology (QIST)
Mar 2023	USA	Canada	Sign Joint Statement
Apr 2023	USA	Neitherlands	Sign Joint Statement of the United States of America and the Netherlands on Cooperation in Quantum Information Science and Technology
Apr 2023	USA	Republic of Korea	Sign Joint Statement on Cooperation in Quantum Information Science and Technology (QIST)
Jun 2023	USA	India	Sign Joint Statement from the United States and India
Sep 2023	USA	India	Sign Joint Statement from India and the United States
Oct 2023	USA	Singapore	SIgn The U.S.-Singapore Critical and Emerging Technology (CET) Dialogue

Figure: International Cooperation Events in 2023

Time	Collaborating Parties		Event
Apr 2023	France	Neithlands	They surround in key economic areas and dual transition towards digitalization and sustainability, as well as the EU's strategic autonomy, structured dialogues are being conducted and public-private cooperation is being strengthened around specific projects. This includes key enabling technologies (semiconductors, quantum technology, photonics), sustainable industries (decarbonization of industrial processes, renewable and low-carbon energy including nuclear and hydrogen, critical and bio-based raw materials, circular economy, decarbonization storage), agriculture and agri-food, and sustainable liquidity.
Jun 2023	Canada	UK	They are strengthening their cooperation in quantum science and technology, promoting the protection and enforcement of intellectual property rights in quantum science and technology. Both countries will support each other in developing markets and strengthening the supply chains for quantum products, while establishing a robust talent pool required for quantum workforce. A joint statement will support Canada's national quantum strategy through increased sharing of expertise and accelerating the development of transformative quantum technologies such as novel computing, secure communication networks, and precise and accurate sensors. Through cooperation among academia, industry, and like-minded nations, Canada will consolidate its leadership position and further strengthen and reaffirm its role as a key player on the global stage of quantum science and technology.
Nov 2023	Rep. of Korea	UK	They are harnessing the potential of key technologies such as artificial intelligence, quantum, and semiconductors to create job opportunities and unleash economic growth. At the same time, they have established a new £4.5 million fund to establish joint research and innovation partnerships.
Nov 2023	Republic of Korea	Japan	They are launching a quantum technology research and development cooperation framework, where the national research institutions of both countries—Japan's National Institute of Advanced Industrial Science and Technology and Republic of Korea's Korea Institute of Standards and Science—will sign a memorandum of understanding.

04 Quantum Policies in 2023

In 2023, a total of 13 countries/organizations worldwide (excluding China) issued policies supporting quantum development. Among them, the European Union issued the most policies, totaling 8. Following closely, the United States issued 7 policies, while the United Kingdom issued 5 policies.

Figure: China's Policies Supporting Quantum Development in 2023

No.	Release Time	Country/ Organization	Publishing Institution	Policy Title
1	Jan 2023	Canda	Innovation, Science, and Economic Development Department	Canada's National Quantum Strategy
2	Jan 2023	USA	NSTC	National quantum initiative Supplement to the president's FY 2023 budget
3	Jan 2023	Germany	PTB	Aufgaben und Ziele der Themenbereiche für 2023-2025
4	Jan 2023	EU	EC	2030 Digital Compass: the European way for the Digital Decade
5	Jan 2023	Canada	Federal Government	The World's First Photonic-based, Fault-tolerant Quantum Computer
6	Jan 2023	Denmark	Ministry of Industry, Commerce, and Financial Affairs; Ministry of Foreign Affairs; Ministry of Defense; Ministry of Defense Higher Education and Science	Danish Quantum Communication Infrastructure project (QCI.DK)
7	Feb 2023	UK	Innovate UK	Innovate UK Transformative Technologies Funding
8	Mar 2023	UK	Department for Science, Innovation & Technology	National Quantum Strategy
9	Mar 2023	Canada	DND/CAF	Quantum 2030
10	Mar 2023	Sweden	VINNOVA	Swedish Quantum Agenda
11	Mar 2023	UK	Ministry of Science, Innovation, and Technology	Science and Technology Framework
12	Mar 2023	UK	Ministry of Science, Innovation, and Technology	The UK's International Technology Strategy
13	Mar 2023	EU	EC	The European Quantum Communication Infrastructure (EuroQCI) Initiative

No.	Release Time	Country/ Organization	Publishing Institution	Policy Title
14	Mar 2023	EU	EC	EuroHPC Joint Undertaking Decision Of The Governing Board Of The Eurohpc JOINT Undertaking No 03/2023 Amending the Joint Undertaking's Work Programme and Budget for the year 2023 (Work Programme and Budget Amendment no. 1)
15	Mar 2023	Canada	DND/CAF	Quantum 2030-Quantum Science & Technology Strategy Implementation Plan
16	Mar 2023	EU	EC	Digital Europe Work Programme 2023-2024
17	Mar 2023	EU	CEN and CENELEC	Standardization Roadmap on Quantum Technologies
18	Apr 2023	Japan	Cabinet Office, Comprehensive Innovation Strategy Promotion Council	Quantum Future Industry Creation Strategy"
19	Apr 2023	India	Cabinet	National Quantum Mission (NQM)
20	Apr 2023	Gerany	Federal Government	Quantum Technology Action Plan
21	Apr 2023	Japan	Ministry of Economic Affairs	Ensuring Stable Supply of Cloud Programs
22	Apr 2023	Australia	Government/Ministry of Industry and Science	Training Australia's world class quantum technology graduates
23	Apr 2023	EU	EC	The European Competence Framework for Quantum Technologies
24	May 2023	Australia	Government	National Quantum Strategy
25	May 2023	UK	Ministry of Science, Innovation, and Technology	National semiconductor strategy
26	Jun 2023	Denmark	Government	National Strategy for Quantum Technology
27	Jun 2023	Republic of Korea	Ministry of Science and Information and Communication Technology	outh Korea's Quantum Science and Technology Strategy
28	Jun 2023	USA	The White House	National Standards Strategy for Critical and Emerging Technology

No.	Release Time	Country/ Organization	Publishing Institution	Policy Title
29	Aug 2023	USA	CISA, NSA, NIST	Migration to Post-Quantum Cryptography
30	Aug 2023	USA	NSF	Expanding Capacity in Quantum Information Science and Engineering (ExpandQISE) program
31	Sep 2023	EU	EU	European Chips Act
32	Sep 2023	USA	United States Department of Commerce	the CHIPS Act
33	Oct 2023	Australia	Queensland Government of Australia	The Queensland Quantum and Advanced Technologies Strategy
34	Oct 2023	Republic of Korea	MSIT	Law on the Promotion of Quantum Science and Technology and Quantum Industry
35	Nov 2023	Ireland	Ministry of Continuing Education and Higher Education, Research, Innovation, and Science	Quantum 2030
36	Nov 2023	USA	House Committee on Science, Space, and Technology	The National Quantum Initiative Reauthorization Act
37	Dec 2023	Europe	EIC	European Innovation Council (EIC) 2024 work programme
38	Dec 2023	EU	The rotating presidency of the European Union, Spain	European Declaration on Quantum Technologies
39	Dec 2023	USA	NSTC	The National Quantum Initiative Supplement to the President’s FY 2024 Budget Released
40	Dec 2023	USA	NSTC	The National Quantum Initiative Supplement to the President’s FY 2024 Budget Released
41	Dec 2023	India	QETCI、MeitY	The Quantum Value Chain Report

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